Adaptations and acute physiological effects of various resistance training programs in adolescent and elite athletes

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Statement of sources

Declaration of author

This thesis is my own work and has not been submitted in any form for another degree or diploma at any university and/or institution. Information derived from the published or unpublished work of others has been acknowledged in the text and a list of references has been provided.

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Declaration on ethics

The research presented in this thesis was conducted in accordance with the research guidelines of the *WORLD MEDICAL ASSOCIATION DECLARATION OF HELSINKI – Ethical Principles for Medical Research Involving Human Subjects* (2008), the *James Cook University Policy on Experimentation Ethics, Standard Practices and Guidelines* (2001), and the *James Cook University Statement and Guidelines on Research Practice* (2001). The research methodology and protocols of each study in the thesis received clearance from the Hames Cook University Experimentation Ethics Review Committee (H3972).

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Statement on the contribution of others

All consumables and equipment used in the thesis were provided by the places of business at which the studies occurred. That is for Chapters 3-5, any equipment and consumables were provided by Aspire Academy, Doha, Qatar. For Chapters 6 and 7 any equipment and consumables were provided by South Australian Sports Institute, Kidman Park, Australia. For Chapter 8 any equipment and consumables were provided by Adelaide Football Club (AFC), Adelaide, Australia.

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Intellectual support	Proposal writing	Dr Glen Deakin (JCU)
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I recognise the editorial assistance of my supervisory team in the publication of Chapters 3 and 6. Below is an account of others' contribution to the completion of these manuscripts.

Chapter Number	Details of publication(s) on which chapter is based	Nature and the extent of the intellectual input of each author, including the candidate
3	Haines, B., Bourdon, P., & Deakin, G. (2016). Reliability of common neuromuscular performance tests in adolescent athletes. *Journal of Australian Strength and Conditioning, 24*(4), 16-22	Haines developed the research question in conjunction with the co-authors. Haines collected the data with assistance of Bourdon. Haines analysed the data, performed the primary data analysis and wrote the first draft of the paper which was revised with editorial input from Deakin and Bourdon.
6	Haines, B., & Deakin, G. (2014). Longitudinal neuromuscular monitoring tool: A case study using bodyweight vs loaded countermovement jump. *Journal of Australian Strength and Conditioning, 22*(5), 37-40	Haines developed the research question in conjunction with Deakin. Haines collected the data, analysed the data, performed the primary data analysis and wrote the first draft of the paper which was revised with editorial input from Deakin.

I declare that all persons whom have provided sufficient contribution to this thesis have been included as co-authors or have been acknowledged in published papers or papers currently under review in peer-reviewed journals.

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Abstract

Introduction: The ability to perform typical athletic movements such as running and jumping is strongly linked with performance outcomes in many sports. Resistance training has been associated with improving these qualities and is commonly used by elite athletes to aid sports performance. Through the careful manipulation of resistance training programs and associated variables, a range of program types can be used by athletes to improve strength and power. As such, the effect of maximum strength or maximum power training programs on sports performance are of great interest. To effectively assess this impact on performance, various body composition, morphological and neuromuscular tests have been utilised. The overall aim of this thesis was to examine the responses, both chronic and acute, of athletes to maximum strength and maximum power training during various preparation and in-season periods. Subsequently, a series of studies were conducted to examine the effects of maximum strength and/or maximum power training on performance in various athlete sub-groups during their normal preparation and competition periods.

In the first study (Chapter 4), the effects of an in-season vs preparation period resistance training program on body composition, muscle morphology and neuromuscular adaptations were investigated in adolescent athletes. The second study (Chapter 5), extended this research, examining the acute neuromuscular effects and recovery profile of adolescent athletes to a fatiguing maximum strength training session at three different periods during their annual training. Study 3 (Chapter 6) examined the use of both a bodyweight countermovement jump CMJ_{BW} and a loaded countermovement jump CMJ_{LOAD} as longitudinal, neuromuscular readiness monitoring tools. The fourth study (Chapter 7) compared the effect of both a maximum strength and maximum power training program on the lower body power of endurance and strength/power athletes. The final study (Chapter 8) examined the effects of an in-season strength/power program on lower body power in elite team sport athletes.

Methods: In Chapter 4, 14 adolescent male athletes performed a nine week in-season maximum strength training program and a six-week, preparation period maximum strength training program. Body composition, morphological and neuromuscular assessments were also conducted before and after both training periods to assess changes over each period. For Chapter 5, the same 14 adolescent athletes performed a fatiguing maximum strength training session consisting of ten sets of five repetitions of back squat at 85% 1RM at various time points throughout the year, i.e. early pre-season (block 1), post a competition period (block 2) and post a six-week maximum strength training preparation period (block 3). To assess the acute neuromuscular effects and recovery profile, a testing battery comprising a countermovement jump (CMJ), drop jump (DJ), isometric mid-thigh pull (IMTP) and 20 m sprint was performed before as well as immediately, 4, 24s, and 48 h post the training session. Chapter 6 assessed

an elite male adult beach volleyball athlete for neuromuscular readiness using a CMJ_{BW} and a CMJ_{LOAD} over a 23-week period. In Chapter 7, five elite endurance athletes (rowers) and five elite strength/power athletes performed a four-week maximum strength program and a four-week maximum power program during a preparation period. To assess the impact of these programs on performance, the athletes were tested using a CMJ_{BW} and a CMJ_{LOAD} (30% 1RM back squat) every week across the training periods. For Chapter 8, the same assessment tools were used as in Chapter 7 however this time the subjects were elite Australian rules football players (n=46) who were assessed in-season.

Results: In Chapter 4, the preparation period maximum strength training block resulted in a very likely small beneficial change in vastus lateralis thickness and 3RM back squat strength and possibly small beneficial changes in multiple CMJ variables. No real effects were observed in any other tests. During the in-season block, likely small beneficial changes in 20-m sprint variables where observed with no other effects found. For Chapter 5, DJ performance showed the greatest fatigue susceptibility following the maximum strength training stimulus with moderate harmful effects on jump height observed immediately post strength training for block 1 and block 2 and 24 h and 48 h post block 1. CMJ also showed fatigue susceptibility, however not to the same extent as the DJ. The IMTP showed a fatigue effect only immediately post the strength training session, whereas the 20-m sprint only showed a fatigue effect after strength training at the end of a competition period. Conversely, the 20-m sprint showed a performance potentiation effect when testing was performed after the athletes had completed a strength training block. In Chapter 6, relative peak power appeared the most accurate measure of training induced neuromuscular fatigue, varying appropriately in relation to training load for both a CMJ_{BW} and CMJ_{LOAD}. Chapter 7 showed that strength/power athletes exhibited greater increases in relative peak power than endurance athletes after the maximum strength block for both the CMJ_{BW} (7.8% ± 4.8%) and CMJ_{LOAD} (5.9% ± 8.3%). After the maximum power block the strength/power athletes showed greater increases compared with endurance athletes both relative peak power and jump height when measured via a CMJ_{BW} (9.8% ± 8.6% and 8.0% ± 6.4% respectively) and a CMJ_{LOAD} (7.0% ± 5.7% and 5.2% ± 4.6% respectively). Chapter 8 found that, CMJ_{BW} and CMJ_{LOAD}, showed similar abilities to detect varying levels of neuromuscular readiness. Performance variables such as relative peak power and jump height showed the most similar patterns of fatigue whilst the technique variable, centre of gravity movement, showed less similarity in the fatigue response.

Conclusion: Adolescent athletes who perform a minimum six-week maximum strength training block will experience improvements in muscle pennation angle, lower body strength (3RM back squat) and CMJ performance whilst a competition block utilising more speed training is likely to see improvements in 20-m sprint time as highlighted by the findings of Chapter 4. Results from Chapter 5 suggest that the DJ is more effected by acute fatigue from a maximum strength training session than either the CMJ, IMTP or 20-m sprint whilst stronger athletes may be less susceptible to the fatigue generated by this type of training. Chapter 6 suggests that the CMJ_{BW} is an appropriate test to monitor the weekly neuromuscular fatigue generated via an athletes' combined training load. Strength/power athletes are likely to see greater gains in CMJ_{BW} and CMJ_{LOAD} variables such as relative peak power and jump height when compared with endurance athletes when both groups perform either a maximum strength or maximum power four-week training block as shown by the results from Chapter 7. Chapter 8 highlights that a CMJ_{BW} and CMJ_{LOAD} show very similar results when tracking the weekly, in-season neuromuscular readiness of elite Australian rules football players with both output and technical execution variables showing similar results.

In summary, strength and power variables as assessed via the above tests show clear but specific effects across, different athlete groups. Specifically, adolescent athletes showed clear adaptations to a six-week maximum strength block and a clear acute response to single maximum strength session. Additionally, strength/power athletes showed a larger performance benefit from both strength and power training compared with endurance athletes. In monitoring performance, the CMJ and associated variables was consistently a valid measure of performance changes over a training cycle and a valid measure of acute neuromuscular readiness.

Practical applications: Maximum-strength and -power training cause different athletic performance changes due to the underpinning effects on muscle and neural physiology. Simple neuromuscular performance tests may be appropriate for assessing these changes, negating the need for invasive or time consuming laboratory based assessments. These effects are also relevant to the type of athlete performing the training program and can result in the following training effects:

1. Adolescents:
    a. A six-week maximum strength training program has beneficial impacts on muscle morphology and multiple neuromuscular performance variables.
    b. Maximum strength training has the largest fatigue effect on DJ performance and less effect on IMTP performance.
    c. Adolescent athletes may be better equipped to deal with the neuromuscular fatigue associated with a maximum strength training session as detected by CMJ, DJ, IMTP and 20 m sprint after performing a six-week strength block.
2. Adult individual sports:
    a. The CMJ_{BW} appears more effective to monitor longitudinal neuromuscular fatigue generated by total training load in a Beach Volleyball athlete than the CMJ_{LOAD} when a taper is included in the monitoring period.

b. Strength/power athletes show better performance benefits when compared with endurance athletes in both the CMJ_{BW} and CMJ_{LOAD} after four-week maximum-strength and -power training blocks performed during their normal pre-season.

3. Adult team sports:
   a. CMJ_{BW} and CMJ_{LOAD} show similar neuromuscular fatigue responses to the demands of, weekly competition of elite AFL athletes.

Publications during candidature

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Chapter 3: Haines, B. Bourdon, P. Deakin, G. Reliability of common neuromuscular performance tests in adolescent athletes. Journal of Australian Strength & Conditioning. 2016;24(4):16-22

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ACSA	Anatomical cross-sectional area
AFL	Australian rules football
BMC	Bone mineral content
BMS	Ballistic measurement system
CAR	Central activation ratio
CG	Centre of gravity
CI	Confidence interval
CMJ	Countermovement jump
CMJ_{BW}	Bodyweight countermovement jump
CMJ_{LOAD}	Loaded countermovement jump
CSA	Cross-sectional area
CV	Coefficient of variation
DEXA	Dual-energy x-ray absorptiometry
DJ	Drop jump
EMG	Electromyography
END	Endurance
ES	Effect size
ICC	Intra-class correlation coefficient
iEMG	Integrated electromyography
IMTP	Isometric mid-thigh pull
ITT	Interpolated twitch technique
LG	Lateral gastrocnemius
MHC	Myosin heavy chain

MPB	Muscle protein breakdown
MPS	Mean protein synthesis
MRI	Magnetic resonance imaging
MS	Maximum strength
MVC	Maximum voluntary contraction
MP	Maximum power
PCSA	Physiological cross-sectional area
PHV	Peak height velocity
RM	Repetition maximum
RFD	Rate of force development
RSI	Reactive strength index
S&C	Strength and conditioning
SD	Standard deviation
sEMG	Surface electromyography
SJ	Squat jump
SSC	Stretch-shortening cycle
STR	Strength
SWC	Smallest worthwhile change
VL	Vastus lateralis

Chapter 1

Introduction

1.1 General response to resistance training protocols

Resistance training is commonly used as a method to enhance performance in a multitude of sports (Baker, 2001; Beattie, Carson, Lyons, & Kenny, 2016; Bennie & Hrysomallis, 2005; Christou, Smilios, Sotiropoulos, Volaklis, Pilianidis, & Tokmakidis, 2006; Harries, Lubans, & Callister, 2016; Hoffman, Ratamess, Cooper, Kang, Chilakos, & Faigenbaum, 2005; Howatson, Brandon, & Hunter, 2016; Suchomel, Nimphius, & Stone, 2016). The physiological adaptations that occur in response to a resistance training program to subsequently drive enhanced sport performance can be divided in to three main areas:

1. Morphological
2. Biochemical
3. Neuromuscular

These adaptations take place over different time courses, and are underpinned by acute responses immediately after a specific training session with acute effects lasting up to 72 hrs post a resistance training session (Gathercole, Sporer, Stellingwerff, & Sleivert, 2015a). Adaptations are wide spread, often involving the interaction of various physiological variables. For example, resistance training has been shown to have a positive impact on muscle hypertrophy with a concurrent increase in anabolic hormone levels (Folland & Williams, 2007). Whilst all three areas of adaptation are of equal importance in understanding the implications for sport performance benefits, this thesis will focus predominantly on the morphological and neuromuscular responses to exercise.

The changes that have been identified in both morphological (Folland & Williams, 2007) and neuromuscular (Folland & Williams, 2007; Gabriel, Kamen, & Frost, 2006) factors have been documented in previous literature and are presented in Table 1.1:

Table 1.1. Morphological and neuromuscular responses to resistance training

Morphological	Neuromuscular
Whole-muscle size	Cross transfer
Muscle fibre hypertrophy	Adaptations in force sensation
Myofibrillar growth and proliferation	Change in antagonist activity
Hyperplasia	Motor unit activation (including):
Fibre type and myosin heavy chain composition	• Firing frequency
Density of skeletal muscle	• Synchronisation
Tendon stiffness and connective tissue arrangement	• Cortical adaptations
Muscle architecture (pennation angle)	• Spinal reflexes

The use of resistance training programs in elite sports may drive changes in movement patterns associated with key outcomes within a specific sport. For example, jump height may be a movement pattern that can provide a competitive advantage over an opponent in sports such as basketball, volleyball and netball. As such the effects of resistance training programs on morphological and neuromuscular responses that culminate in an improved jump height over time are of great value. These resistance training programs typically focus on two main qualities that underpin general sporting task performance (Suchomel et al., 2016). First, maximum strength which can be described as the muscles ability to exert force on an external object (Stone, 1993) and second, maximum power or 'explosive' muscle strength, commonly defined as the rate of rise in contractile force (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002a). Accordingly, the effects of both maximum strength and maximum power training on morphological and neuromuscular acute responses and longer-term adaptations have been a focus of scientific research (Folland & Williams, 2007; Kyröläinen et al., 2005).

1.1.1 Acute responses to various resistance training protocols

Maximum strength and power training are commonly referred to in the literature as 'neuronal schemes' (Crewther, Cronin, & Keogh, 2006) as it is hypothesised that they improve strength and power predominantly via changes in neuromuscular pathways. As such a large body of research exists examining acute neuromuscular responses (Bosco, Colli, Bonomi, von Duvillard, & Viru, 2000;

Brandon, Howatson, Strachan, & Hunter, 2015; Howatson et al., 2016; Linnamo, Häkkinen, & Komi, 1997; Linnamo, Newton, Häkkinen, Komi, Davie, McGuigan, & Triplett-McBride, 2000; McCaulley, McBride, Cormie, Hudson, Nuzzo, Quindry, & Travis Triplett, 2009) when compared with that investigating acute morphological responses. The bulk of this research has utilised laboratory based tests such as isometric maximal voluntary contractions (MVC) with subsequent electromyography (EMG) analyses as the assessment tool (Brandon et al., 2015; Linnamo et al., 1997; McCaulley et al., 2009) post training. These studies suggest that maximum strength training may have a greater effect on neuromuscular readiness than maximum power training with peak force recovering faster than rate of force development (RFD). The use of only isometric measures to track neuromuscular performance whilst accurate in detecting neuromuscular changes, provides limited information to applied practitioners who are more likely interested in the effects on dynamic movements.

Brandon et al. (2015) examined neuromuscular responses during dynamic exercise via EMG and found that a maximum strength training session resulted in similar levels of neuromuscular recruitment and power generation but produced greater levels of fatigue when compared with maximum power training. This provides useful insight into acute responses during a maximum strength or power training session for the applied practitioner.

Limited research exists on the recovery time course from either a maximum strength or power program. Howatson et al. (2016) have shown that MVC remains depressed up to 24 h post a maximum strength session but is not effected by a maximum power session. This complements the previous research on acute responses (Brandon et al., 2015; Linnamo et al., 2000; McCaulley et al., 2009) and indicates that the neuromuscular fatigue generated by a strength session is generally, greater than and longer lasting than a maximum power session.

This is valuable knowledge to the practitioner as it helps them better understand the short term physiological effects maximum strength or power training has on neuromuscular variables, specifically those related to resistance training. However, the daily/weekly preparation of elite athletes involves a range of complex physical activities that involve running and jumping and as such may respond to neuromuscular fatigue differently when compared with gym-based resistance training.

As such, performance tests are now commonly being used to assess neuromuscular fatigue in various sports given the similarities in movement patterns (Cormack, Newton, & McGuigan, 2008c; Johnston, Cook, Drake, Costley, Johnston, & Kilduff, 2016; Ronglan, Raastad, & Børgesen, 2006; Wiewelhove, Raeder, Meyer, Kellmann, Pfeiffer, & Ferrauti, 2015). The benefits of using these performance tests to monitor neuromuscular fatigue is that they provide a valid, reliable measure (Gathercole et al., 2015a) that requires minimal familiarisation and produces minimal fatigue, thus limiting their impact on sport-specific training or competition (Gathercole et al., 2015a). Given the common acceptance of performance tests, such as the countermovement jump (CMJ), drop jump (DJ) and sprints, in assessing neuromuscular fatigue, it could be hypothesised that these tests would also prove to be beneficial and practical diagnostic tools when examining the effect of various resistance training protocols on neuromuscular fatigue.

1.1.2 Chronic adaptations to various resistance training protocols

When examining adaptations to resistance training it is reported in the literature that changes in muscle cross-sectional area have been noted as early as 20 days into a training program (Seynnes, de Boer, & Narici, 2007). As such, research examining the chronic effects of maximum strength or power training should utilise a minimum time frame of four weeks and may last two years or more. Given the longer time frames associated with chronic adaptation training studies and the minimum time frames required for muscle morphological changes, a substantial body of research exists examining the effects of maximum strength and power training on morphological and neuromuscular adaptations (Campos et al., 2002; Cormie, McBride, & McCaulley, 2009; Cormie, McGuigan, & Newton, 2010; Folland & Williams, 2007; Hakkinen, Pakarinen, Alen, Kauhanen, & Komi, 1988; Kyröläinen et al., 2005; Lyttle, Wilson, & Ostrowski, 1996; McGuigan, Sharman, Newton, Davie, Murphy, & McBride, 2003; Narici et al., 1996; Østerås, Helgerud, & Hoff, 2002; Rønnestad, Kojedal, Losnegard, Kvamme, & Raastad, 2012; Schmidtbleicher, 1987; Winchester, McBride, Maher, Mikat, Allen, Kline, & McGuigan, 2008). This research has focussed on morphological adaptations predominantly via muscle fibre type (Campos et al., 2002; Kyröläinen et al., 2005; McGuigan et al., 2003; Winchester et al., 2008), size (Campos et al., 2002; Kyröläinen et al., 2005) and myosin heavy chain (MHC) isoform composition (Campos et al., 2002; Kyröläinen et al., 2005; McGuigan et al., 2003) and neuromuscular changes via specific neuronal mechanisms such as RFD, peak fore and EMG (Cormie et al., 2009; Cormie et al., 2010; Hakkinen et al., 1988; Kyröläinen et al., 2005; Schmidtbleicher, 1987) or general performance measures (Lyttle et al., 1996; Østerås et al., 2002).

The research examining morphological adaptations suggests that maximum strength training (Campos et al., 2002) has direct effects on many of the variables noted above. These changes are a shift of fibre types from IIB towards type IIAB seen after training, shifts in MHC expression from MHCIIB towards MHCIIA and increases in the cross-sectional area of the three major fibre types (I, IIA and IIB) whilst power training (Kyröläinen et al., 2005; McGuigan et al., 2003; Winchester et al., 2008) has no effects. The downside of this type of analyses is that it requires a muscle biopsy which may be detrimental to athletes in a daily training environment. In contrast, more recent research by Cormie et al. (2010) used ultrasound to explore changes in muscle thickness and pennation angle and average muscle mass via dual-energy x-ray absorptiometry (DEXA) scans in both maximum strength and maximum power trained subjects. They found positive changes in muscle mass, muscle thickness and pennation angle following a maximum strength block whilst only pennation angle showed any change in the power training group although this was only seen after 10 weeks. This less invasive analyses method may be very beneficial in quantifying the changes in skeletal muscle in athletes in response to targeted resistance training programs.

Conversely, neuromuscular adaptations to either resistance training protocol shows varying effects. Schmidtbleicher (1987) reported improvements in peak force after both resistance training programs but found a larger increase in RFD after maximum strength versus maximum power training. Kyröläinen et al. (2005) reported an increase in plantar flexor isometric MVC after power training with no change in RFD whilst the knee extensors showed no change in MVC but an increase in RFD. Whilst Hakkinen et al. (1988) found no change in maximal isometric leg extension peak force and EMG after two years of training in elite weightlifters. The variation in results from these studies highlights the challenges associated with comparing neuromuscular adaptations across research with different experimental variables including subject experience, length of the training study and the assessment tool used.

A more simple and valid assessment method may be the effect of maximum strength and maximum power training on adaptations to commonly used performance tests that underpin the athletic movements seen in many sports. This also provides the applied practitioner with direct information on the effect of these same training methods, i.e. maximum strength or maximum power training, on neuromuscular performance tests that involve similar muscle patterns to sporting movements such as jumping (vertical power), sprinting (horizontal power) and the compound movement, lower body strength, that underpins power activities. Tests that have been most commonly used to assess impact on performance are the CMJ (Byrne & Eston, 2002; Cormie et al., 2009; Cormie et al., 2010; Gathercole, Stellingwerff, & Sporer, 2015b; Rønnestad et al., 2012; Sheppard, Cronin, Gabbett, McGuigan, Etxebarria, & Newton, 2008b; Winchester et al., 2008) , DJ (Byrne & Eston, 2002; Sheppard et al., 2008b; Viitasalo, Salo, & Lahtinen, 1998), sprints (Christou et al., 2006; Lyttle et al., 1996; Seitz, Reyes, Tran, de Villarreal, & Haff, 2014; Wang et al., 2016) , and isometric mid-thigh pull (IMTP) (Haff, Stone, O'Bryant, Harman, Dinan, Johnson, & Han, 1997; McGuigan & Winchester, 2008; McGuigan, Winchester, & Erickson, 2006; Stone et al., 2003; Wang et al., 2016). This substantial body of research has shown that using these tests to assess performance changes is a reliable and valid method to quantify the effects of various athletic training methodologies, including resistance training, which may subsequently have a beneficial impact on sporting performance.

1.1.3 The effects of resistance training on the adolescent athlete

In the quest to discover the next talented athlete, adolescent athletes are a focus of talent development programs. As such, younger athletes are being exposed to all the demands of adult sport including competition and training. This has resulted in adolescent athletes being exposed to resistance training protocols used by adult athletes such as maximum strength and maximum power training without the same level of scientific research into the effects on the adolescent athlete that exists in adult athletes. For the purpose of this thesis, the term adolescent refers to the period of age between 14-18 years for males as has been used in previous literature (Behm, Faigenbaum, Falk, & Klentrou, 2008; Faigenbaum, Kraemer, Blimkie, Jeffreys, Micheli, Nitka, & Rowland, 2009). Although this is a common age grouping reserved for adolescent males, it presents some limitations such as the differences observed in physical development found between the chronological age and biological age of the athlete (Malina, Eisenmann, Cumming, Ribeiro, & Aroso, 2004; Sherar, Esliger, Baxter-Jones, & Tremblay, 2007).

Initial research in this area focussed more on adolescents with limited or no resistance training experience (Chelly, Fathloun, Cherif, Amar, Tabka, & Van Praagh, 2009; Christou et al., 2006) and developing position statements for general resistance training guidelines for adolescents (Baker et al., 2011; Faigenbaum et al., 2009; Lloyd et al., 2012). Both research based on inexperienced resistance trained adolescents and general resistance training guidelines are of little value in understanding the effects of maximum strength and maximum power training on trained adolescent athletes. Whilst studies exist examining the effects of maximum strength and power training on adolescent athletes with prior resistance training experience (Drinkwater, Lawton, Lindsell, Pyne, Hunt, & McKenna, 2005; Pullinen, Mero, Huttunen, Pakarinen, & Komi, 2002) substantial gaps still exist in the literature. The limitations of using research in novice resistance trained athletes and the use of various 'non-traditional' strength/power protocol highlights the need for further research. Additionally, a lack of research examining the acute neuromuscular responses and the recovery period post maximum strength training is an area that requires additional research to provide the applied practitioner with a better understanding of the recovery time course and aid in the structuring of weekly training.

1.2 Statement of the problem

Previous research on the acute response of maximum strength training and maximum power training in elite athletes has focussed predominantly on changes in laboratory based measures such as maximal voluntary contractions MVC and EMG. Limited research exists detailing the effects using performance based neuromuscular tests such as the CMJ. Specifically, the weekly adaptations of these types of programs across a training block has not been investigated, leaving it unclear for the practitioner on how these changes are occurring across a training block and if they are similar amongst different cohorts of elite athletes. That is, do strength / power based athletes respond the same as endurance based athletes, or what response do weekly competing field-based athletes have when performing in-season strength/power training?

Additionally, the acute effects and recovery time course of elite adolescent athletes to maximum strength training at different periods during the annual cycle has not been investigated. Similarly, the adaptations that occur across in-season and preparation periods in elite adolescent athletes has not been investigated previously and remains unclear for applied practitioners working with this age-group.

1.3 Aims of the thesis

The overall aim of this thesis was to examine the neuromuscular and/or morphological effects of various resistance training protocols commonly used in athletic development in elite, adolescent and adult athletes at various timepoints throughout a training year. As such, the thesis was separated into five studies with the following aims:

1. To examine the neuromuscular and morphological adaptations to both a pre-season and in-season maximum strength resistance training protocol in elite adolescent athletes.
2. To examine the acute neuromuscular fatigue and recovery responses in elite adolescent athletes following maximum strength training at three different periods within the annual cycle.
3. To examine the effectiveness of two different CMJ's to assess longitudinal neuromuscular fatigue.
4. To examine the lower body power, and associated adaptations of strength/power and endurance athletes to both a maximum strength and maximum power, four-week training block.
5. To examine the weekly neuromuscular responses of elite Australian rules football players during a 5-week in-season strength training program.

1.4 Research questions

1. Will pre-season maximum strength training result in greater neuromuscular and morphological adaptations than in-season maximum strength training?
2. Will a maximum strength protocol elicit different acute fatigue responses and recovery dynamics:
    a. in various neuromuscular tests (i.e. CMJ, DJ, IMTP and 20-m sprint)? And
    b. at various points throughout the annual training cycle (i.e. competition period, and early- and late-preparatory period)?
3. Will different CMJ's and their associated variables exhibit different neuromuscular fatigue responses based on an athletes recent training demands?
4. Will elite strength/power athletes have greater gains in performance than elite endurance athletes when performing similar maximum strength or maximum power training blocks and will both groups achieve greater gains in lower body power performance from maximum power compared with maximum strength training?
5. Will elite Australian rules football players see changes in neuromuscular responses during a 5-week in-season period?

1.5 Significance of the study

This series of studies aims to increase the understanding of acute responses from a single session and chronic adaptations across multiple sessions to various resistance training protocols used by elite athletes (adolescent and adult), thus benefiting the applied practitioner. Strength and conditioning (S&C) coaches could use the findings from Chapter 3 to confidently and accurately design a maximum strength training program to improve this important quality in athletic performance. Additionally, based on Chapter 4, practitioners could better plan a training week for adolescent athletes. The results of this study provide new information on adolescent acute responses to maximum strength training at different times throughout the annual training cycle and enhances our understanding of recovery timeframes for various neuromuscular performance tasks regularly used in isolation or combined in weekly sport training in adolescent athletes.

The studies focussed on adult athletes provide novel information on the weekly changes in lower body power in response to maximum strength or maximum power training in elite strength/power and endurance athletes competing in peaking sports (Chapter 7), whilst Chapter 8 provides novel information on the in-season weekly responses for elite, team sport athletes.

Collectively, the findings from these studies allow practitioners to more precisely plan resistance training blocks/sessions dependant on the neuromuscular response they are seeking. The novel information presented in these studies gives clarity around the acute responses following a single training session and the subsequent adaptations across a training block. Additionally, the studies provide significant insight into various neuromuscular monitoring tools that may be used to track performance changes over a training block or to monitor acute neuromuscular readiness at any time point during the athletes training cycle.

1.6 Delimitations

The current adolescent athlete studies (i.e. Chapters 3, 4 and 5) were delimited to:

1. Trained adolescent male athletes (14-18 y) who were at least six months post-PHV (peak height velocity), training for their chosen sport a minimum of eight sessions per week with a minimum of two years' resistance training experience. Therefore, the findings may not be extrapolated to other population groups (i.e. inexperienced resistance trained adolescent athletes or adolescent athletes who have not clearly finished their PHV period).
2. Body composition, morphological and neuromuscular performance variables. The assessment methods chosen whilst typical in athletic assessment were not exhaustive therefore the extrapolation of the findings to other assessment tools may not be applicable.
3. Time frame. Both the 6-week training adaptation study and the 48 h acute response study time frames are specific to the assessment periods used and the findings may not be applicable to other training adaptation studies or acute response studies using different time frames.

The current adult athlete studies (i.e. Chapters 6, 7 and 8) were delimited to:

1. Trained adult athletes who train for 25 h or more in their chosen sport, are competing at a high level and have extensive sport-specific and resistance training history.
2. Lower body power jump assessments and variables (i.e. bodyweight countermovement jump (CMJ_{BW}) and loaded countermovement jump (CMJ_{LOAD}) at 30% 1RM). The effect of strength training on jumping performance in either a CMJ_{BW} or 30% 1RM CMJ_{LOAD} may not be the same as other lower body power assessment tools.
3. The four-week maximum strength and maximum power training block used. Extrapolation of these findings to alternative length training blocks may not be applicable.

1.7 Limitations

The findings of the current studies were limited by:

1. Sample size was limited to available athletes within each squad who volunteered for the study and performed all the required training and testing sessions.
2. Subjects were not a random sample of the athletic population but volunteers from the respective elite sporting organisations used in the studies.
3. Standard technical and biological variability. To limit the impact of such change, tests were conducted at the same time of day on the same day of week where possible, all equipment was calibrated prior to use and warm-ups prior to testing were standardised.

1.8 Format of the thesis

The first chapter of this thesis provides a brief introduction of acute and chronic responses to resistance training in an athlete population and the associated issues with the current research project. Chapter 2 is a literature review that introduces the general physiological responses to resistance training. The focus of the review is the variation that exists in physiological response to various resistance training and the lack of research examining specific responses in elite adolescent and adult athletes.

Chapters 3 to 5 were all conducted on elite adolescent athletes. Chapter 3 reports the reliability of the neuromuscular tests used to assess the adolescent athletes in Chapters 4 and 5 as no previous reliability data exists for these tests (CMJ, DJ, IMTP and 20-m sprint), within this specific population group. Chapter 4 examined the adaptations to a maximum strength program across a training block whilst Chapter 5 assessed the acute responses to a maximum strength training session.

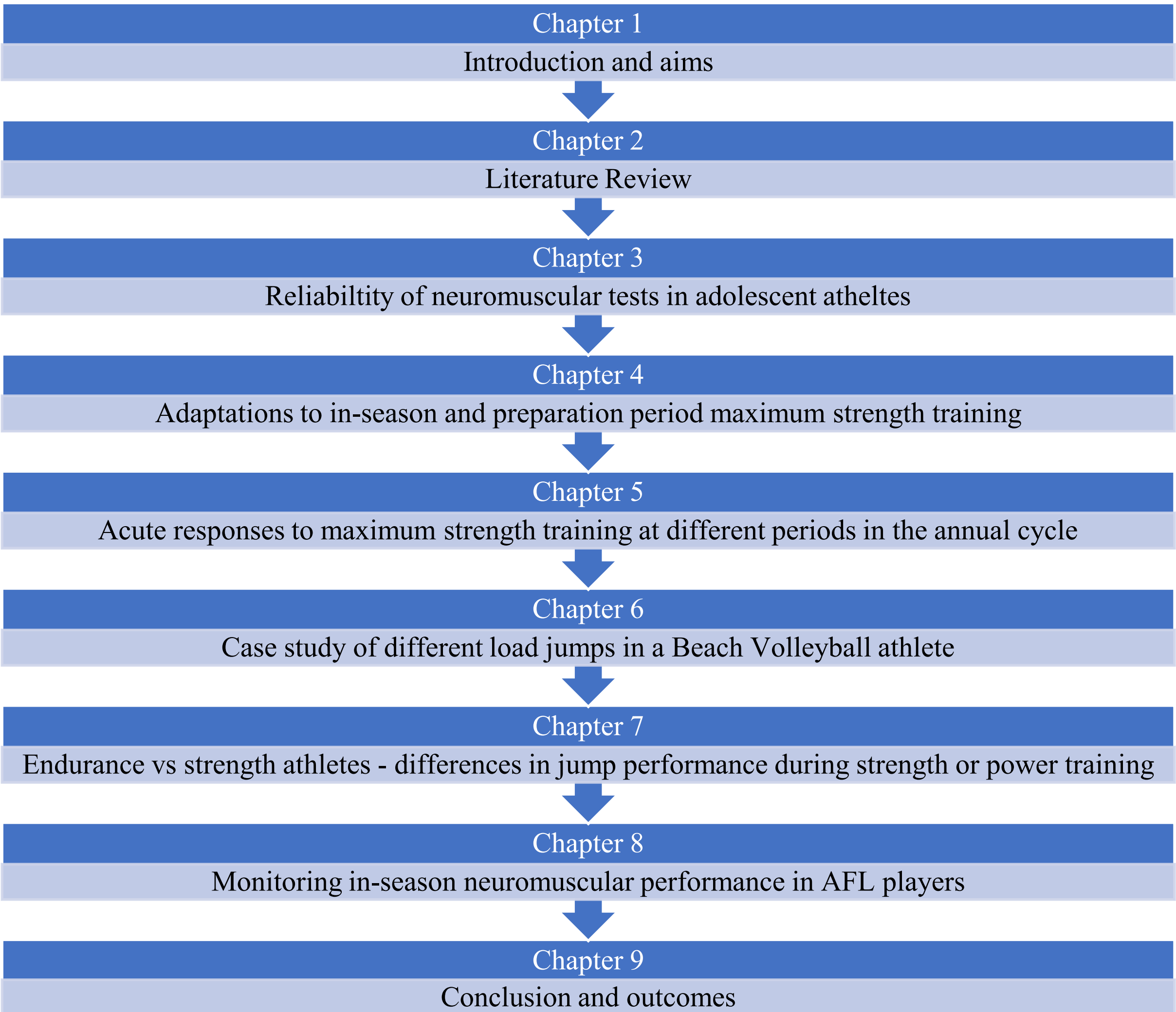
Chapter 6 is shorter than the other studies as it was a case-study examining the validity of two neuromuscular tests to be used in subsequent studies and was required as no previous data existed.

Chapter 7 compared the effects of either a maximum strength or maximum power training block on neuromuscular performance in elite athletes from physiologically different sports and training backgrounds. Chapter 8 examined the weekly neuromuscular response to an in-season maximum strength/power program performed by elite Australian rules football players.

All studies were designed and performed to provide greater insight into the physiological response and/or adaptations to typical training programs used in the athletic preparation of elite athletes. As such they were all written in the style typical of journal articles and are in various stages of publication. Chapters 3 and 6 have been accepted and published in peer-reviewed journals whilst Chapters 4, 5, 7 and 8 are currently under review in peer-reviewed journals.

During this thesis, the author relocated internationally from Qatar to Australia due to a change of employment. Accessibility to trained adolescent athletes changed as a result of this move so the initial specific focus of the thesis, adolescent athletes, had to be broadened to include adult athletes. Additionally, due to a change in the equipment available for athlete assessment, the morphological and neuromuscular assessment tools used were narrowed.

The flow chart below provides a visual representation of the structure of the thesis.



Chapter 2

Literature Review

Due to the wide range of training induced response and adaptations that can occur in different age groups as well as a result of the resistance training protocol used, this review first examines the general guidelines for resistance training before delving into physiological responses. When examining the physiological changes associated with resistance training, this chapter firstly reviews the overarching chronic adaptations that occur at a morphological, biochemical and neuromuscular level before examining potential acute responses that happen post training and underpin these adaptations. Whilst this thesis does not examine the biochemical responses to maximum strength or maximum power training in either adolescent or adult athletes, the importance of biochemical variables in these responses and adaptations is accepted in the literature and as such has been included below although as not to the same detail as the morphological and neuromuscular changes.

2.1 General resistance training protocols

Resistance training is a common exercise methodology used by the general population for health benefits and aesthetic purposes. In an athletic population, it is used to enhance targeted physical characteristics that may result in beneficial effects on performance in their given sport. Resistance training is typically characterised by the following variables which can be manipulated in designing a program (Kraemer & Ratamess, 2004):

- Exercise – The general type of movement chosen to target a specific muscle or group of muscles.
- Exercise order – The sequence in which exercises are placed across a single training session.
- Repetitions – The number of times a specific exercise is performed without resting (reps).
- Sets – The number of times the group of repetitions is repeated.
- Load – The resistance used during the exercise. This is also referred to as intensity and is typically displayed as a percentage of the heaviest weight a subject can lift once (one repetition) in the chosen exercise (% 1RM).
- Speed – Also known as repetition velocity, this is the velocity that a repetition is performed at.
- Rest periods – The period of rest between the completion of one set and commencing a subsequent set.

- Frequency – The number of training sessions performed during a uniform block of time, i.e. during one week.

These variables can be manipulated to cause specific physiological changes within the body depending on whether the goal is hypertrophy, strength, power or endurance. General guidelines of these variables have been provided in previous literature and are summarised in tables 2.1-2.3 below (Kraemer & Ratamess, 2004).

Table 2.1. Program variable guidelines and progressions for hypertrophy training. Adapted from Kraemer & Ratamess, 2004.

	Novice	Intermediate	Advanced
Intensity (% 1RM)	60-70	70-80	70-85
Volume (sets × reps)	(1-3) × (8-12)	(Multi) × (6-12)	(Multi) × (6-12)
Rest periods (min)	1-2	1-2	1-3
Velocity	Slow to moderate	Slow to moderate	Slow to fast
Frequency (days/week)	2-3	2-4	4-6

Table 2.2. Program variable guidelines and progressions for strength training. Adapted from Kraemer & Ratamess, 2004.

	Novice	Intermediate	Advanced
Intensity (% 1RM)	60-70	70-80	70-100
Volume (sets × reps)	(1-3) × (8-12)	(Multi) × (6-12)	(Multi) × (1-12)
Rest periods (min)	1-2	1-3	~ 3
Velocity	Slow to moderate	Moderate	Slow to fast
Frequency (days/week)	(2-3)	(2-4)	(4-6)

Table 2.3. Program variable guidelines and progressions for power training. Adapted from Kraemer & Ratamess, 2004.

	Novice	Intermediate	Advanced
Intensity (% 1RM)	30-70	30-80	30->80
Volume (sets × reps)	(1-3) × (8-12)	(1-3) × (3-6)	(3-6) × (1-6)
Rest periods (min)	1-3	1-3	>3
Velocity	Moderate	Fast	Fast
Frequency (days/week)	2-3	2-4	4-6

As highlighted by the authors, different guidelines are necessary for people of different levels of experience, i.e. novice, versus intermediate, versus advanced (Kraemer & Ratamess, 2004). This is due to the body's adaptation to a given training stimulus over time, thereby requiring a greater stimulus to continue the adaptive process. Figure 2.1 below shows a typical physiological response to an imposed stimulus and highlights an initial level of performance to which a stimulus is applied, resulting in a short-term decrement to performance before undergoing a supercompensation period which results in a new level of performance being achieved (Zatsiorsky & Kraemer, 2006).

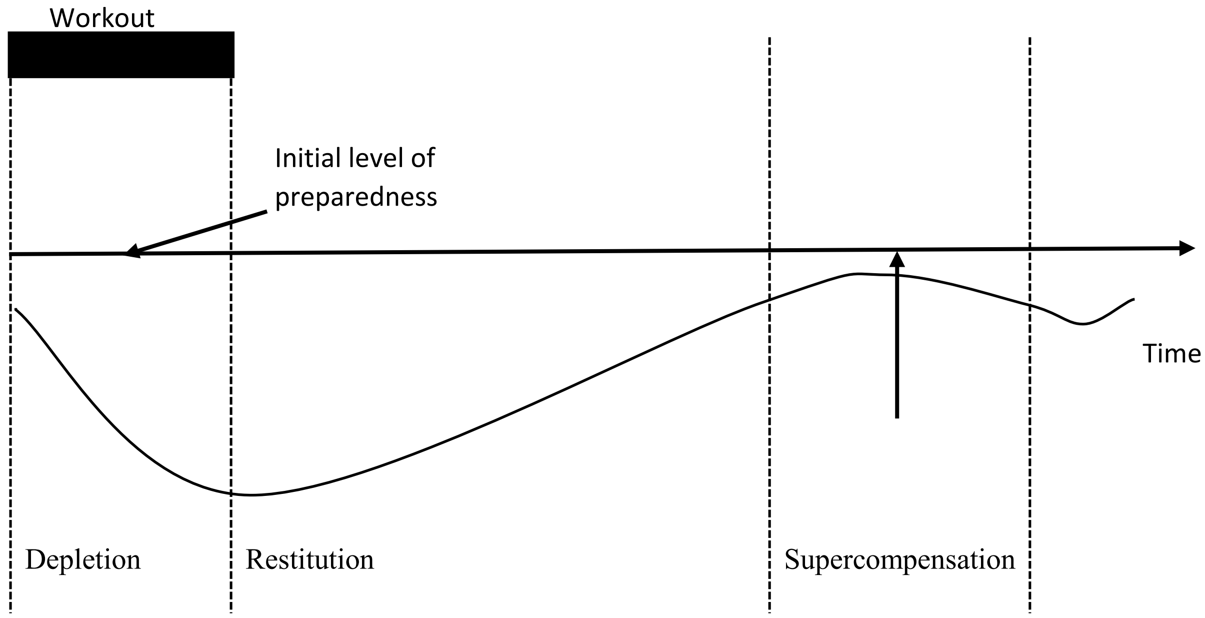


Figure 2.1. Theory of supercompensation time course. If an additional stimulus is applied at the correct time, i.e. as performance level peaks, the stimulus required to produce a similar depletion, restitution and therefore, supercompensation is greater. Adapted from Zatsiorsky & Kraemer (2006).

Once this first stimulus or exercise session is completed, the adaptation sequence begins initiating a time-course adaptation that is specific to the individual and the exercise protocol used. (Kraemer, Fleck, & Evans, 1996). For example, if a resistance training protocol utilising programming variables that target strength is chosen, various physiological adaptations will occur resulting in a higher level of strength performance at the completion of the program (Kraemer & Ratamess, 2004). Specifically, cellular and molecular responses to strength training are dictated by the combination of program design variables used and thereby underpin associated adaptations (Bickel, Slade, Mahoney, Haddad, Dudley, & Adams, 2005). These adaptations and responses are detailed later in this review. The magnitude of increase seen in performance varies across different population groups and even across individuals within groups (Asçi & Açikada, 2007). As an individual performs regular strength training and experiences the associated gains in strength, the training stimulus they require to continue to experience these performance benefits moves from the classifications of novice, through intermediate and if performed long enough, to advanced. This then requires the individual to provide a stronger stimulus than when they were classed as novice trainers by manipulating the variables shown in Table 2.2 such as intensity, volume, rest and frequency. As such, due to their accumulated history of resistance training, most elite athletes should be considered as advanced with respect to these guidelines (Ahtiainen & Häkkinen, 2009; Baker, 2001; Peterson, Rhea, & Alvar, 2005).

Within an athletic population, the ability to run faster, jump higher/longer, change direction more quickly and complete any other number of athletic movements is beneficial across a range of sports. As such any training modality that improves these qualities is of benefit. Resistance training has been associated with improvements in these qualities and as such, a large body of research has focussed on the general effects of resistance training on athletic performance and more specifically, the link between specific strength/power and athletic performance (Baker, 2001; Beattie et al., 2016; Cormie et al., 2010; Harries et al., 2016; Lyttle et al., 1996; McBride, Triplett-McBride, Davie, & Newton, 1999; Østerås et al., 2002; Sheppard, Cormack, Taylor, McGuigan, & Newton, 2008a; Stone et al., 2003; Suchomel et al., 2016).

In targeting improvements in athletic performance, it is necessary to understand which effect a resistance training program (hypertrophy, strength, power or endurance) will have on performance. An example of this is a recent article which reviewed the importance of muscular strength in athletic performance (Suchomel et al., 2016). The authors suggested that stronger athletes outperformed weaker athletes in sport-specific performance measures from both strength/power and endurance based sports. Sports studied included, cycling, boxing, ice hockey and endurance runners amongst others and show the breadth and impact that strength can have on sporting performance. Indeed, some recent studies suggest that maximum strength and maximum power training may have the largest benefits on physiological characteristics that contribute to athletic performance and thereby enhance sport performance (Cormie et al., 2010; Suchomel et al., 2016)

It is therefore unsurprising that most resistance training programs utilised by athletes throughout the year focus on developing both maximum strength and maximum power qualities. However, the placement of these types of training in an athletes annual training cycle must be planned carefully to ensure, a) that the athlete is not subject to a stimulus they are not prepared for and is subsequently injured or does not achieve the desired performance gains, or b) is not placed in a state of fatigue that compromises competition performance. As such, these resistance training programs are planned and organised throughout the year to maximise performance and minimise fatigue in a concept known as periodisation (Fleck, 1999; Harries, Lubans, & Callister, 2015; Rhea & Alderman, 2004).

2.1.1 Periodisation of resistance training for the athlete

As detailed above, various resistance training schemes exist to target certain physiological outcomes, i.e. hypertrophy, strength, power or endurance. Whilst all these may provide some benefit to overall sporting performance, the time spent on each type of training scheme and the appropriate placement of these training schemes within the athlete’s yearly calendar are critical to proper preparation. The organisation of these planned variations of training variables (i.e. volume, intensity, frequency, etc.), aimed at maximising performance gains and minimising fatigue is termed periodisation and is commonplace in athletic preparation (Harries et al., 2015; Rhea & Alderman, 2004). The practical example of these forms of planned variation is the manipulation of volume and intensity throughout an athlete's season which may contain multiple phases (Baker, 2001). These phases are dependent upon the number and length of competitive periods within the annual calendar and vary across sport type (e.g. individual versus team sport) and level of competitiveness (adult versus junior). The overall goal of periodisation should be to provide a framework of structured training phases to divide the yearly calendar into smaller, more manageable time frames for which appropriate training can be planned (Fleck, 1999; Issurin, 2010). The first step in developing the training plan is to determine the three phases of training that are common to all sports and athletes which are preparatory, competitive and transition (off-season) with an example shown in Figure 2.2 (Bompa, 1999). Once these three phases are determined, the practitioner may then divide the training plan into shorter periods such as mesocycles consisting of approximately three to six weeks and microcycles ranging from four to ten days, dependant on the training schedule or competition requirements, i.e. days between competition of their specific sport (Issurin, 2010). This provides a conceptual framework for organising the specific resistance training schemes as mentioned above to ensure the athlete is in peak physical condition when competing (Graham, 2002).

Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	June	July	Aug.	Sep.	Oct.
Preparatory phase				Competitive phase							Transition

Figure 2.2. Typical periodisation model for athletes competing in the Australian Football League

Variations in resistance training design are common when comparing preparatory versus competitive phase programs. Typically, the higher volume, moderate intensity of hypertrophy training occurs earlier in the annual training plan preceding the lower volume, higher intensity of maximum strength and maximum power training closer to the beginning of the competitive phase and a further reduction in volume once the competitive period begins. This organisation of the training schemes is referred to as linear periodisation and is characterised by this linear reduction in volume and concurrent increase in training intensity (Harries et al., 2015; Rhea, Ball, Phillips, & Burkett, 2002). In contrast, an undulating or non-linear periodisation model incorporates more frequent manipulations of training variables, either daily or weekly and is proposed to enhance strength/power gains via a more frequent change in training stimulus (Harries et al., 2015; Rhea et al., 2002). A recent meta-analysis of linear and undulating periodised resistance training programs by Harries et al. (2015) found no difference in the effectiveness of either model in developing muscular strength. This potentially indicates that the inclusion of some type of periodisation or variation in the annual training cycle of athletes may be more critical to maximising adaptation to training than the periodisation model chosen. Indeed, modern periodisation models have evolved to meet the demands of modern day sport which include factors such as an increase in number of competition days (Issurin, 2010). The traditional linear periodisation model as mentioned above has been complemented by more complex/dynamic methods of organising training units such as block periodisation and concentrated loading periods (Issurin, 2010). As such, S&C coaches are implementing these mixed-model periodisation strategies in the real world in an attempt to develop appropriate physical qualities over one or more training years and to peak these physical qualities multiple times throughout a year. The diverse range of sports, competition models and range of athlete i.e. adult versus adolescent requires substantial research to examine the effect of these training manipulations on short and long-term performance.

Whilst a significant body of research exists examining the effects of different types of general periodisation strategies in adult athletes (Bartolomei, Hoffman, Merni, & Stout, 2014; Graham, 2002; Harries et al., 2015; Monteiro, Aoki, Evangelista, Alveno, Monteiro, Piçarro, & Ugrinowitsch, 2009; Rhea & Alderman, 2004; Rhea et al., 2002), limited research exists examining the use of pre-season and in-season strength training programs in adult and adolescent athletes across a range of sports and requires further attention.

2.2 General physiological responses to resistance training

To better understand the performance benefits seen across multiple sports and their movements in relation to resistance training, researchers have attempted to isolate the individual and combined physiological responses to resistance training. As a result, a large body of research exists examining the physiological effects of resistance training on the human body including morphological (Ahtiainen, Pakarinen, Alen, Kraemer, & Häkkinen, 2003; Alegre, Jiménez, Gonzalo-Orden, Martín-Acero, & Aguado, 2006; Brandenburg & Docherty, 2002; Folland & Williams, 2007; Hakkinen, Kallinen, Komi, & Kauhanen, 1991; Holm et al., 2008; Kawakami, Abe, Kuno, & Fukunaga, 1995; Kyröläinen et al., 2005; McGuigan et al., 2003; Narici et al., 1996; Raastad, Glomsheller, Bjøro, & Hallén, 2001; Rønnestad et al., 2012; Schmidtbleicher, 1987; Seynnes et al., 2007; Vissing et al., 2008; Winchester et al., 2008) neuromuscular (Aagaard et al., 2002a; Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002b; Ahtiainen & Häkkinen, 2009; Bastiaans, Diemen, Veneberg, & Jeukendrup, 2001; Beattie et al., 2016; Bosco et al., 2000; Brandenburg & Docherty, 2002; Brandon et al., 2015; Buckthorpe, Pain, & Folland, 2014; Byrne & Eston, 2002; Folland & Williams, 2007; Gabriel et al., 2006; Hakkinen et al., 1988; Howatson et al., 2016; Kyröläinen et al., 2005; Linnamo et al., 1997; Linnamo et al., 2000; McCaulley et al., 2009; Narici et al., 1996; Raeder, Wiewelhove, De Paula, Kellmann, Meyer, Pfeiffer, & Ferrauti, 2016; Raeder et al., 2015; Remaud, Cornu, & Guével, 2010; Schmidtbleicher, 1987; Walker, Davis, Avela, & Häkkinen, 2012) and biochemical (Bosco et al., 2000; Fry, Kraemer, Stone, Koziris, Thrush, & Fleck, 2000; Hakkinen & Pakarinen, 1993; Hakkinen et al., 1988; Kraemer et al., 1992; Kraemer et al., 1991; Kraemer et al., 1998a; Kraemer et al., 1990; Kraemer & Ratamess, 2005; Kraemer, Volek, Bush, Putukian, & Sebastianelli, 1998b; Linnamo, Pakarinen, Komi, Kraemer, & Häkkinen, 2005; McCaulley et al., 2009; Ojasto & Hakkinen, 2009; Pullinen et al., 2002; Pullinen, Mero, MacDonald, Pakarinen, & Komi, 1998; Raastad, Bjøro, & Hallen, 2000; Smilios, Pilianidis, Karamouzis, & Tokmakidis, 2003; Uchida, Aoki, Navarro, Tessutti, & Bacurau, 2006) acute responses and chronic adaptations. These effects are wide spread, involving the interaction of various factors. For example, resistance training has been shown to have a positive impact on muscle hypertrophy with a concurrent increase in anabolic hormone levels and strength (Folland & Williams, 2007). The complexity of human physiology can be displayed by the large number of different physiological responses within each physiological system.

This review will discuss both the adaptations and acute responses to resistance training with a focus on maximum strength and maximum power protocols. For this review, chronic adaptations refer to the body's changes in relation to multiple stimuli over time, whereas acute responses refer to the body's changes in relation to a single stimulus. With this in mind, acute responses to a single resistance training bout may last as long as 72 h post stimulus (Gathercole et al., 2015a) and chronic adaptations have been tracked over time periods of up to at least two years (Hakkinen et al., 1988).

Chronic physiological adaptations to resistance training have long been an area of scientific interest. As such, a significant body of literature exists examining the human body's chronic adaptations to various resistance training protocols (Ahtiainen et al., 2003; Campos et al., 2002; Folland & Williams, 2007; Hakkinen et al., 1988; Häkkinen, Pakarinen, Kraemer, Häkkinen, Valkeinen, & Alen, 2001; Hakkinen, Pakarinen, Kraemer, Newton, & Alen, 2000; Kyröläinen et al., 2005; McGuigan et al., 2003; Narici et al., 1996; Rønnestad et al., 2012; Vissing et al., 2008; Winchester et al., 2008). Both maximum strength and power training protocols are planned regularly throughout the yearly training calendar in the pursuit of improved athletic ability. As such understanding the morphological, biochemical and neuromuscular adaptations associated with each training type is critical for program design. The literature below presents a review of these adaptations and highlights areas that have not yet been investigated.

2.2.1 Morphological changes and adaptations to a strength or power program

Morphological changes due to resistance training are well accepted in the scientific literature and are most commonly depicted by the changes in whole-muscle size that occur after resistance training (Folland & Williams, 2007; Wernbom, Augustsson, & Thomeé, 2007) due to its ease of measurement. Muscle hypertrophy and other morphological muscle adaptations have not traditionally been associated with maximum strength or power training protocols. Typically, resistance training protocols that utilise a higher volume and moderate intensity are used when morphological adaptations such as increased cross-sectional area are the goal. However, a small body of research has examined the effect of maximum strength and power training on morphological parameters. The list of morphological adaptations associated with resistance training is significantly more extensive than hypertrophy alone and can include changes in (Folland & Williams, 2007):

- Whole-muscle size
- Muscle fibre hypertrophy
- Myofibrilliar growth and proliferation
- Hyperplasia
- Fibre type and MHC composition
- Density of skeletal muscle
- Tendon stiffness and connective tissue arrangement
- Muscle architecture (pennation angle)

Within these individual adaptations, great variation in response can occur due to the unpredictability of inter- and intra-individual responses and the challenges associated with many of these measurements. Whole muscle size measurement involves either computerised tomography, magnetic resonance imaging (MRI) or ultrasound and can be measured via either physiological cross-sectional area (PCSA) or anatomical cross-sectional area (ACSA) (Folland & Williams, 2007). They differ in that PCSA is measured perpendicular to the line of pull of the muscle fibres whereas ACSA is measured directly across the muscle at its widest anatomical point irrespective of muscle fibre pennation angle (Folland & Williams, 2007). PCSA is deemed the more valid measure of cross sectional area, however both methods are commonly used in the literature (Folland & Williams, 2007). This is due to the challenges of the precise measurement required of variables such as fibre pennation, muscle volume and fibre length estimation, associated with PCSA (Aagaard et al., 2001). Other confounding factors in the reporting of changes in whole muscle size include, muscle group trained, gender, age and even selective muscle growth. Narici et al (1996) found differences in rectus femoris change in cross sectional area (CSA) of between 19% and 50% dependant on where the measurement was taken along the muscle however the training program used in this study did utilise a lifting intensity and repetition volume not commonly associated with maximal strength training.

Changes in muscle CSA as a result of chronic strength training is thought to be primarily driven by muscle fibre hypertrophy (Jones, Rutherford, & Parker, 1989). Due to the number of different types of muscle fibres and their individual properties, this also adds to the variability in response to a resistance training stimulus. Campos et al (2002) reported the preferential hypertrophy of type IIB fibres in response to an eight week resistance program resulting in increases of 12.5% for type I, 19.5% for type IIA and 26% for type IIB. Their study included low repetitions, medium repetitions and high repetition groups with the low repetition group performing a typical maximum strength program consisting of three to four sets of three to five repetitions at an intensity of 3-5RM with three minutes rest between sets performed two to three times weekly for eight weeks. The results of this study suggest that the maximum strength program had a beneficial effect on muscle fibre CSA.

However, the research surrounding morphological changes to muscle have not been limited to hypertrophy with a growing body of literature examining muscle fibre type composition via changes in the expression of MHC composition. In the same study (Campos et al., 2002) the researchers also investigated the effects of the eight-week maximum strength training protocol on MHC isoform composition. The authors found adaptations in MHC isoforms with significant decreases and increases in MHCIIb and MHCIIa isoforms, respectively. This finding is important as it suggests the possibility of achieving positive morphological adaptations whilst utilising maximum strength training protocols of lower volume than hypertrophic protocols.

In research examining the morphological adaptations of human muscle to power training there has been less clear findings. McGuigan et al. (2003) examined the effects of an eight-week power training (jump squat) program on fibre type and MHC isoform composition. The study used two experimental groups, one training at 30% of their 1RM Back Squat and the other group at 80% 1RM. During the training period, subjects trained twice weekly with the volume of both the experimental and control groups varying. No specific data on the total volume performed by either training group was given however, from the information provided it can be assumed that the group that trained at the higher intensity performed less volume. No differences were found in either fibre type or MHC isoform type in either of the two experimental groups indicating that the power training protocols of both light and heavy load had no effect on the morphological parameters measured.

Subsequent research into chronic adaptations has substantiated these findings (Kyröläinen et al., 2005; Winchester et al., 2008). Kyröläinen et al. (2005) investigated the changes in muscle structure after a 15-week power training program utilising various power exercises. Needle biopsies were obtained from the middle portion of the gastrocnemius muscle before and after the training period to allow analysis of muscle fibre type and size and MHC isoform composition. No effects were found for any of the morphological variables measured despite increases in some of the neuromuscular parameters assessed including DJ height and knee extension maximal RFD. Additionally, Winchester et al. (2008) found no change in muscle fibre type distribution in the vastus laterals muscle after eight weeks of jump squat training performed three times per week.

The combined results of these studies suggest that whilst maximum strength training may affect morphological changes, power training protocols do not affect morphological variables. These findings suggest that if morphological changes are a desired outcome from a resistance training program, a maximum strength program may provide sufficient stimulus to drive such adaptations whereas a power program may not. These morphological changes may result in altered force production characteristics of the muscle which may in turn have a positive impact on performance related activities.

2.2.2 Biochemical changes and adaptations to a strength or power program

As with the above morphological research, biochemical responses and adaptations to resistance training have been substantially researched (Ahtiainen et al., 2003; Gonzalez, Hoffman, Stout, Fukuda, & Willoughby, 2016; Hakkinen et al., 1988; Häkkinen et al., 2001; Hakkinen et al., 2000; Kraemer et al., 1999; Uchida et al., 2006). However, the number of hormones within the body, their dependency on each other and the effect of hormone precursors means that the analysis of specific hormonal responses and the effect they have on the body is challenging. Common biochemical parameters linked with resistance training can be found below (Crewther et al., 2006; Kraemer & Ratamess, 2005):

- Testosterone
- Growth hormone
- Insulin-like growth factor 1
- Cortisol
- Catecholamines: Dopamine, Adrenaline, Noradrenaline
- Serotonin
- Creatine Kinase

In addition to the various biochemical parameters effected by resistance training programs, the interplay of other variables adds further complexity to the biochemical response that can be expected from one or more bouts of resistance training. The most important of these is resistance exercise program design, however other factors such as age, gender, nutrition, training status and circadian rhythm can also impact the response (Crewther et al., 2006; Kraemer & Ratamess, 2005). Whilst a full review of the biochemical responses to resistance training is beyond the scope of this chapter, specific studies relevant to maximum strength and power training have been presented below to complement the information presented in previous sections.

Although a substantial body of research exists examining biochemical adaptations to resistance training, the majority of this research has focussed on hypertrophic training schemes with considerably less literature available regarding maximum strength or maximum power training (Ahtiainen et al., 2003; Hakkinen et al., 1988; Kraemer et al., 1999). In one of the few studies to examine the hormonal responses to the specific resistance training protocols of interest Hakkinen et al. (1988) examined the hormonal adaptations of elite weightlifters over a two-year training period. Over the training period a significant increase in resting serum testosterone was found with no changes in cortisol levels observed showing that elite athletes may gain positive benefits in basal hormone levels after a chronic maximum strength/power training period. However, the content of the training over this period was described in general terms of 'they trained for weightlifting' stating that they performed a variety of common power training and maximum strength training exercises. This general training information results in it being difficult to draw any meaningful conclusions on the effectiveness of specific maximum strength or maximum power training on hormonal adaptations.

Ahtiainen et al. (2003) examined the effects of a 21-week resistance training program on hormonal adaptation in strength trained and untrained men. However, the resistance training program was referred to as a protocol used in previous research (Hakkinen et al., 2000) and utilised an intensity of between 50-80% 1RM, loads that cannot be included in maximum strength research. Additionally, heavy resistance and 'explosive' strength training regimes were used concurrently during this exercise program making it impossible to separate the effects either protocol may have had on the variables assessed. Similarly, Kraemer et al. (1999) compared hormonal levels in younger and older men after a strength/power training block. However, as in the previous study the resistance training protocol used both a blended training program with the subjects performing one day of maximum strength, one day of hypertrophy and one day of power training per week. As above, this makes it impossible to separate the effects of either maximum strength or power training on hormone levels.

The scarcity of research on adaptations in hormone levels following a maximum strength or maximum power training protocol leaves a gap in the literature that should be addressed. Further research into the chronic biochemical adaptations of elite athletes to either maximum strength or power training is warranted to gain greater insight into these potential changes and their impacts on performance.

2.2.3 Neuromuscular changes and adaptations to a strength or power program

Neuromuscular adaptations following maximum strength or power training has received significant attention in the literature (Cormie et al., 2009; Cormie, McCaulley, & McBride, 2007a; Cormie et al., 2010; Hakkinen et al., 1988; Kyröläinen et al., 2005; Lyttle et al., 1996; Østerås et al., 2002; Schmidtbleicher, 1987; Winchester et al., 2008). However, the neuromuscular tests used and variables monitored within each to assess adaptations vary greatly giving a wide range of results that are challenging to compare. Some tests and variables are more mechanism driven, using laboratory based assessments to examine variations in variables such as RFD, peak force and EMG activity (Cormie et al., 2009; Hakkinen et al., 1988; Schmidtbleicher, 1987) whilst others focus on the effects on common performance measures such as the CMJ, DJ, IMTP and sprints (Cormie et al., 2010; Lyttle et al., 1996; Winchester et al., 2008).

Previous research has detailed possible mechanisms that may be positively affected by resistance training (Folland & Williams, 2007; Gabriel et al., 2006) including:

- Cross transfer
- Adaptations in force sensation
- Change in antagonist activity
- Motor unit activation
    - Firing frequency
    - Synchronisation
    - Cortical adaptations
    - Spinal reflexes

Understanding and accounting for the neuromuscular adaptations to resistance training are important due to the difference in timeframe and magnitude of muscle strength increases versus the changes in morphological changes, such as CSA, found in scientific studies (Folland & Williams, 2007). Neuromuscular activation is complex, involving multiple variables from both central and peripheral factors. Typically, these two areas are differentiated by changes in processes either above the neuromuscular junction (central) or below (peripheral) and can be observed by changes in motor neuron or excitation-contraction coupling as respective examples (Carroll, Taylor, & Gandevia, 2017).

Changes in neural drive, as measured by increases in EMG, have been postulated as a potential source of early strength gains in response to a resistance training stimulus (Gabriel et al., 2006). A person's ability to voluntarily activate all available muscle fibre's has been investigated previously using the interpolated twitch technique (ITT) and may be a contributor to positive performance adaptations (Brandon et al., 2015; Howatson et al., 2016; Knight & Kamen, 2001). Knight and Kamen (2001) found that an additional electrical stimulation applied on top of a MVC resulted in adults producing 3-5% more maximal force. Additionally, a six-week resistance training program utilising a hypertrophy based scheme an effect on muscle activation was observed, with an improvement of 1.7% in central activation ratio (CAR) (Knight & Kamen, 2001).

Motor unit firing frequency has also been proposed as a mechanism of resistance training based strength gains (Gabriel et al., 2006; Kamen & Knight, 2004). Kamen and Knight (2004) found that younger adults had a higher motor unit firing rate than older adults although no change was found between baseline testing and after a six-week resistance training program. This program did not utilise a typical maximum strength or power scheme and as such, whilst it presents interesting information on general resistance adaptations the results have limited application to the majority of resistance training utilised in athlete physical preparation.

The changes in neuromuscular activation mentioned above may be caused by different mechanisms such as changes in motor cortex signals or spinal reflexes and remains a subject of debate (Aagaard et al., 2002b; Carroll, Riek, & Carson, 2002; Gabriel et al., 2006). Due to the challenges in assessing the specific mechanisms of neuromuscular adaptations to resistance training, research investigating the training effects of maximum strength and power have focussed on accepted variables such as MVC and EMG as detailed below.

Schmidtbleicher (1987) used an isometric MVC of the triceps brachii to investigate maximal RFD, maximal force and EMG analysis in a bespoke apparatus that allowed isometric and concentric shot put movement of the arm. Two groups, maximum strength and maximum power, trained four times weekly across a 12-week period. The strength group training consisted of seven sets of three repetitions or less at intensities of ≥90% MVC, whilst the power training group performed five sets of eight repetitions at a set intensity of 45% MVC. Peak force increased similarly for both groups, 18% and 17% respectively, however RFD showed a much larger increase for the maximum strength group (34%) versus the power group (11%).

In a similar study, Kyröläinen et al. (2005) examined the effects of a power training on neuromuscular performance. Recreationally trained adult males trained twice weekly for fifteen weeks and performed weighted jump squats and other various stretch-shortening cycle (SSC) exercises. The training protocol consisted of a variety of unloaded single and double leg hopping and hurdle jumps, loaded (30-60% 1RM back squat) jump squats and DJs. Knee and plantar flexor isometric MVC's and EMG were assessed for changes in performance as was maximal effort DJ from 50 centimetres. The tests were performed pre-training and after five weeks, ten weeks and post-training (15 weeks). An increase in plantar flexor MVC was observed by the ten-week test as was an increase in EMG however no additional changes were observed by the 15-week test. No change in knee extensor MVC or EMG were observed at any time point despite an increase in maximal RFD. The cumulative effects on performance resulted in DJ height improving over the course of the experimental period. The authors suggested that the increases seen in both DJ performance and plantar flexor MVC and EMG as opposed to knee extensor changes highlight the role of specificity in the adaptations mirroring the muscle groups most directly targeted by the training protocol. This study however must be interpreted with caution as the subjects were recreationally trained and despite undergoing a two-week preparatory phase, would likely respond differently to the training program used compared to trained athletes.

Most training studies investigate the chronic training effects over a training period from between 8-16 weeks. However, Hakkinen et al. (1988) examined neuromuscular adaptations over a two-year training period in elite male weightlifters following a predominantly power training program. Maximal isometric leg extension performance (peak force and EMG) and maximal static squat jumps at a range of additional loads were assessed for changes in performance (jump height). Although performance varied during the period, there was no clear effect on any of the variables measured between the first and last measurements. A small increase in weightlifting performance was seen indicating that any change in performance may have been due to technical improvements. Additionally, the authors noted that the lack of clear effects on neuromuscular performance could be due to the elite training status of the athletes as compared with less-trained or even untrained subjects.

In designing either maximum strength or maximum power training programs to target performance benefits in athletes, strength and conditioning coaches will schedule these sessions amongst the other weekly training commitments of the athletes including their sport specific technical and tactical training sessions. The cumulative effects of each individual session result in the longer-term adaptations seen over a training cycle as described earlier in section 2.1. However, each individual session contributes a certain level of fatigue and depending on the training stimulus given, the athlete undertaking the training will exhibit their own unique recovery profile. As such, it is important to consider and understand the consequences, positive and negative, associated with performing a maximum strength or maximum power training session.

2.3 Acute responses and recovery dynamics to various resistance training protocols in adults

Various resistance training protocols such as maximum strength and power training result in different acute physiological responses and recovery dynamics (Brandon et al., 2015; Howatson et al., 2016). An understanding of these acute responses and recovery dynamics is important when designing resistance training programs for athletes with a specific physiological goal in mind. Not only do these acute responses potentially drive the longer-term chronic adaptations that are sought for performance benefits but the acute effects may also have positive or negative implications for other concurrent training that is occurring within the athlete's weekly schedule such as technical/tactical training. The following section examines the literature surrounding the acute morphological and neuromuscular responses and recovery dynamics to both maximum strength and power training in an athlete population.

2.3.1 Acute morphological responses

As mentioned previously, changes in whole-muscle size is an extensively researched area due to the link between muscle size and strength. General consensus is that 8-12 weeks of resistance training is needed to see substantial changes in muscle size (Folland & Williams, 2007). However, changes in CSA have been noted as early as 20 days in to a training program (Seynnes et al., 2007). However, this time course remains well outside an acute response window and as such, this adaptation has not been a topic of focus in acute responses to resistance training. Despite the overwhelming body of research examining the chronic adaptations associated with resistance training, the literature agrees that this process begins at a molecular and cellular level within hours of cessation of a training session (Bickel et al., 2005).

The significant markers driving morphological changes in skeletal muscle following resistance training are muscle protein synthesis (MPS) and muscle protein breakdown (MPB), a net positive protein balance being required to induce hypertrophic changes (Damas, Phillips, Vechin, & Ugrinowitsch, 2015). MPB shows less variation in response to resistance training in comparison to MPS, resulting in most research focussing on MPS as the key monitoring variable (Damas et al., 2015). Resistance training is recognised to have a strong stimulation effect on MPS and a less powerful effect on MPB, resulting in this net positive protein balance occurring. Chelsey et al. (1992) examined the effect of a hypertrophy training program on MPS rate at 4 h and 24 h post exercise utilising four sets of 6-12 reps at 80% 1RM. They found that MPS rates were elevated post-exercise at both time points compared with the non-exercise control, highlighting the benefit of resistance training on MPS and therefore muscle hypertrophy.

Damas et al. (2015) recently published a review comparing the magnitude and time course of MPS in untrained versus trained resistance exercise subjects. The authors concluded that resistance trained individuals experience a faster peak in MPS post-exercise compared with untrained counterparts. However, the peak change in MPS was less than that experienced by the untrained subjects, additionally, the rate of decay of MPS occurred more quickly in the trained group resulting in the untrained group experiencing an approximate three-fold greater increase in MPS in the 48 h period after a resistance training session. These results are congruent with the impaired hypertrophy adaptations seen in trained versus untrained individuals to a hypertrophy-based resistance training program (Ahtiainen et al., 2003).

This provides further evidence of the need for the more advanced program variables used in resistance training programs for individuals with an extensive training history such as an athletic population (Ahtiainen et al., 2003).

In a further attempt to understand the acute morphological responses to resistance training, creatine kinase has been used as a marker to indicate muscle damage from resistance training that is linked to protein turnover and remodelling (Soares, Mota, Duarte, & Appell, 1996). Whilst this topic is relevant to morphological changes, due to the multi-factorial relationship between resistance training, muscle damage and protein synthesis, creatine kinase will be discussed in further detail in the acute biochemical response to resistance training section (2.3.2) below. As detailed above, acute morphological responses to resistance training, specifically the effect of various training protocols such as maximum strength and maximum power remain poorly understood and would benefit from additional research to aid the design and planning of resistance training programs for athletes.

2.3.2 Acute biochemical responses

The focus of this literature review is on the morphological and neuromuscular adaptations and responses to maximum strength and power training as has been detailed above. However, the acute morphological responses are linked with the acute biochemical responses and as such it is important to understand these acute biochemical responses to resistance training.

A large body of scientific literature is available examining the biochemical response to maximum strength training compared with power training. The number of biochemical parameters that have been studied are extensive and their responses vary greatly both within and between resistance training protocols. Adding to the confusion is the number of different factors that can affect acute responses such as program design, sex, age, previous training history and nutrition (Crewther et al., 2006). Due to these confounding factors, previous scientific literature has found mixed biochemical responses to both maximum strength (Hakkinen & Pakarinen, 1993; Kraemer et al., 1998a; Raastad et al., 2000) and power training (Bosco et al., 2000; Crewther et al., 2006; Izquierdo, Ibanez, Hakkinen, Kraemer, Ruesta, & Gorostiaga, 2004).

In examining the biochemical response of adult males to maximum strength training, Kraemer et al. (1990), manipulated training intensity and rest periods of a typical 5RM maximum strength program and examined blood lactate, serum testosterone, serum human growth hormone and serum insulin-like growth factor 1. Biochemical responses were measured immediately, 5, 10, 15, 30, 60, 90 and 120 minutes post training. They utilised a ‘primary’ training program consisting of a whole-body workout of eight exercises that the subjects performed 3-5 sets of at 5RM with three minutes rest between sets. The intensity and rest period were then manipulated in subsequent sessions by either decreasing the intensity and increasing volume to 10RM, or decreasing the rest period to one minute between sets. The primary strength program significantly increased blood lactate levels immediately post as well as 5 and 15 minutes post-exercise. When rest was shortened, blood lactate was significantly higher compared with normal resting conditions at zero and five minutes post. Conversely, when rest was maintained and load was decreased, no effects on blood lactate when compared with resting values were seen. A similar response was seen in testosterone levels with both the primary strength program and shortened rest program showing significant increases in testosterone levels when compared with normal resting whilst the decreased load program showed no effects. Human growth hormone and insulin like growth factor 1 showed more inconsistent results varying in response across time points however in general, the higher volume, lower intensity program appeared to have greater effect on both these hormones. This suggests that typical maximum strength training intensities of 5RM or higher have significant effects on testosterone and less effect on human growth hormone and insulin-like growth factor 1 in male adults. In a follow up study, Kraemer et al. (1993) repeated their research on female adults. Interestingly, no changes were found in testosterone and insulin-like growth factor 1 highlighting the different hormonal responses between male and female adults when exposed to the same maximum strength stimulus.

Hakkinen and Pakarinen (1993) examined acute responses in human growth hormone, testosterone and cortisol to a workload of 20 sets of one repetition at 100% of 1RM. No significant changes in serum testosterone concentration, serum free testosterone or cortisol concentration were found immediately post, the morning after, and 2 mornings after exercise. As highlighted by the authors this indicates that hormonal response to resistance training is dependant not only on the workload performed but on the intensity/volume breakdown of the resistance training and in this case, the use of a very heavy load (1RM) and a total volume of 20 reps with three-minute rest periods was not sufficient to induce changes in the hormones examined.

In similar maximum strength research, Smilios et al. (2003) examined the effects of varying volume and intensity of a maximum strength protocol on biochemical markers including blood lactate, serum testosterone, serum cortisol and human growth hormone. Volume and intensity was varied by subjects performing exercises of either two, four or six sets of five repetitions at intensities ranging between 79 % and 88% of 1RM. Blood analysis performed pre, immediately post, 15 and 30 minutes post-exercise showed that blood lactate increased significantly immediately post-exercise at all time points when compared with pre-workout levels, regardless of the number of sets performed. Interestingly, no change was seen in serum testosterone for any protocol at any of the time points despite the fact that increased blood lactate levels stimulates testosterone secretion in the Leydig cells (Raastad et al., 2000). Human growth hormone showed increases immediately post all sessions with the four-set protocol showing higher responses than the two-set protocol, whilst cortisol concentrations decreased significantly after all the exercise sessions with no difference between protocols. Conversely, in a study by Zafeiridis, Smilios, Considine & Tokmakidis (2003) using four sets of five repetitions at 88% 1RM, no significant changes in cortisol levels were found whereas a significant increase in blood lactate levels was found immediately after resistance training, returning to baseline levels by 30 minutes post-exercise.

Raastad et al. (2000) examined acute hormonal response and recovery dynamics in adult males following two differing maximum strength training protocols. The 'heavy' protocol utilised a load of 100% of the corresponding RM for each exercise whilst the 'moderate' protocol utilised a load of 70% of the corresponding RM. The same set and repetition scheme was used for each group and the rest period between sets was also the same. Testosterone increased significantly more immediately post the heavy protocol compared with the moderate protocol whilst cortisol decreased significantly more after the moderate protocol. Human growth hormone response was similar between the two groups although this showed the greatest inter-individual differences. These varied findings in the hormonal responses to maximum strength training reinforce the influence of confounding factors as mentioned previously, especially program design including exercise selection, volume, intensity and overall workload.

The body of research examining the acute hormonal responses to maximum power training is significantly less than that performed on maximum strength training. In one such study, Bosco et al. (2000) examined acute hormonal response following various maximum strength and power training protocols. Male track and field sprinters performed maximum strength training comprising of 6 series of 16 repetitions (6+6+4 reps, 3 minutes rest between sets) at 80% 1RM, whilst two groups of Olympic Weightlifters performed different power training protocols performing either ten sets of 2-3 repetitions at 60-80% 1RM or 20 sets of 2-4 repetitions at 50-70% 1RM. The maximum strength session resulted in significant decreases in testosterone and cortisol immediately post-exercise. Conversely, the higher intensity power training group experienced a significant increase in testosterone post-exercise with no changes in cortisol levels, whilst the lower intensity power training group had no changes in either hormone. These results are interesting because they highlight the difference in responses between three neuronal resistance training protocols, even within a similar training scheme as seen with the two power training groups. The decrease in testosterone seen in the maximum strength group is contrary to the effects seen in the previous studies (Kraemer et al., 1990; Raastad et al., 2000), however this may be due to the very high volume of repetitions performed (96), which is higher than the volumes typically performed in maximum strength training programs. McCaulley et al. (2009) examined acute testosterone, cortisol and blood lactate responses immediately post, one, 24 and 48 h post-exercise following a single bout of both maximum strength and power training. The maximum strength training protocol consisted of 11 sets of three repetitions of the parallel back squat at 90% 1RM with five-minute rest periods between sets whereas the power training protocol consisted of eight sets of six jump squats at body mass with three minute rest periods. No significant changes were observed in the raw hormone data for either group at any time point although trends of a higher percentage increase in testosterone pre- to immediately post-exercise were found for the maximum strength versus power group whereas a larger percent decrease was found in the power group. Only blood lactate showed a significant increase during the study, exclusive to the maximum strength training group immediately post-exercise.

The body of research examining catecholamine response to maximum strength or power training is limited, especially when compared to the hormone research presented above. In addition, the use of alternative training protocols not typical of those used in maximum strength or power training make the findings from this literature challenging to apply in a practical setting (Pullinen et al., 2002; Pullinen et al., 1998). The research highlights that resistance training influences catecholamine response, with Pullinen et al. (1998) finding that a training protocol of 10 sets of five repetitions of bilateral leg extensions performed with one minute rest between sets increased both adrenaline and noradrenaline post-exercise, whilst extending the rest periods to four minutes resulted in an increase in noradrenaline only. Other catecholamine's requiring further research include dopamine and serotonin due to their proposed role as possible markers in central fatigue (Meeusen, Watson, Hasegawa, Roelands, & Piacentini, 2006).

The large variance in acute biochemical responses in adults to a maximum strength or maximum power training sessions is apparent and requires further research to provide more specific guidelines for applied practitioners.

2.3.3 Acute neuromuscular responses

Maximum strength and power training is commonly referred to in the literature as 'neuronal schemes' (Crewther et al., 2006) as it is hypothesized that they improve strength and power predominantly via changes in neuromuscular pathways as opposed to morphological adaptations. As discussed previously, morphological changes take at least three weeks to occur after commencing a resistance training program (Seynnes et al., 2007). However, gains in strength during resistance training are noted to occur earlier. In conjunction with this, strength training appears to result in disproportionately larger increases in muscle strength than size (Behm et al., 2008), further increasing interest in the neuromuscular responses to strength training. As such, acute neuromuscular responses have been a focus of previous research with the literature investigating two distinct areas, neuromuscular responses (Bosco et al., 2000;

Brandon et al., 2015; Linnamo et al., 2000) and neuromuscular fatigue (Howatson et al., 2016; Linnamo et al., 1997; McCaulley et al., 2009). In general, neuromuscular response studies have detailed the immediate effect, positive or negative, of strength or power training sessions on subsequent performance whilst neuromuscular fatigue literature has examined the time course of the recovery of these measures.

Of interest to the applied practitioner are any differences in acute responses to typical resistance training protocols. The research summarised below details the differences and similarities that have been found in acute neuromuscular responses to either maximum strength or maximum power training.

Previous research examining the acute neuromuscular response to training has typically utilised a time course ranging from immediately post-exercise up to 72h post exercise (Gathercole et al., 2015a). Linnamo et al. (1997) investigated neuromuscular fatigue following a power training protocol in male and female subjects. Their protocol comprised of 5 sets of 10 bilateral leg extension performed as explosively as possible. Intensity of the exercise was difficult to ascertain as no absolute intensity was provided by the authors. Maximal peak force and maximal RFD measured via a maximal bilateral isometric leg extension test were both significantly lower immediately following exercise with peak force recovering to baseline levels 1 h post, whilst maximal RFD required 2 h to return to pre-training levels. In addition, integrated electromyography (iEMG) activity of the vastus medialis, vastus lateralis and rectus femoris was also examined and, for the time period of 0-100 ms of the movement, was still found to be depressed two days after exercise in males. In contrast to this, the female group showed a full recovery of iEMG activity within 1 h of having completed the exercise indicating potentially different neuromuscular responses between genders to power training. The recovery of maximal peak force and RFD were similar to that found in the male group indicating that although males had recovered force production qualities in a similar time frame, the mechanism for developing the force was different due to the depressed iEMG activity. In a follow up study, Linnamo et al. (2000) examined the neuromuscular response to power training via concentric only incline leg press. Subjects performed the same volume as in the previous study however the exercise examined was changed to an incline leg press that utilised a computer controlled braking system to eliminate the eccentric component of the movement. The load used for training was 40 ± 6% of the subject's isometric maximum at a knee angle of 100°. In contrast to their previous work, no significant decreases in neuromuscular responses were found leading the authors to suggest the lower volume, propagated via the lack of an eccentric portion of the movement, as a possible mechanism for these findings.

In examining the acute neuromuscular response to a maximum strength training protocol, Bosco et al. (2000) tested the leg extensor muscles of male and female sprinters whilst performing a maximal dynamic half-squat and a full squat training session. Average power output, measured in a full and half-squat, was found to decrease in the male sprinters during the session whilst the females showed no decrease in power output for either lift. EMG analysis of the leg extensor muscles showed no significant changes for either group in the full-squat over the exercise period, however significant decreases in EMG activity were found for both groups during the training session. As above, the different neuromuscular response between male and female athletes is of great interest showing potentially different responses to resistance training. The decrease in power output during the full-squat shown by the males with EMG activity remaining unchanged indicates that peripheral fatigue may have been more heavily affected than neural factors. This response was in direct contrast to that found after power training by Linnamo et al. (1997) where force output recovered quickly but EMG remained depressed suggesting different acute responses to the two resistance training protocols. However, caution must be used when interpreting these results, as different athlete groups, subjects and exercise selections were used adding unknown variation. Additionally, in the Bosco study, training volume consisted of six sets of 16 repetitions with eight minutes rest between sets. Each set of 16 repetitions was broken into smaller sets of six, six and four reps with three minutes rest between smaller sets resulting in a total 96 reps performed across the session. Whilst significant rest was given between efforts, the total volume for this type of training stimuli is very large. Additionally, no clear idea of training load/intensity was given, making it impossible to determine whether this protocol was targeting maximum strength, or maximal power adaptations and therefore whether a larger morphological or neuromuscular response was expected.

In a study examining both maximum strength and power training groups, McCaulley et al. (2009) investigated the acute neuromuscular response in an isometric squat following a single bout of either maximum strength or power training. The maximum strength protocol consisted of 11 sets of three repetitions of the back squat performed at an intensity of 90% 1RM with five minutes rest between sets, whilst the power training group performed eight sets of six repetitions of a jump squat with no external load and a between set rest period of three minutes. The study found a significant decrease in peak force and rate of force development immediately following the maximum strength protocol and again at 1h post exercise. Additionally, maximum RFD was still depressed 24 h post-exercise whilst peak force had returned to pre-exercise levels. Conversely, the power group exhibited no significant changes in the isometric squat for either peak force or maximum RFD. In contrast, the authors reported a non-significant trend as peak force surpassed that recorded in the rest condition group at 1, 24 and 48 h post the power training protocol suggesting a possible potentiating effect from the power training.

Brandon et al. (2015) also investigated the neuromuscular responses of elite athletes to various resistance training protocols. However, this study utilised the same ten elite track and field athletes to perform 10 sets of five maximal squat repetitions, with three minutes rest between sets, at either heavy (85% 1RM), moderate (75% 1RM) or light (50% 1RM) loads, potentially allowing for greater accuracy in comparing results between the different loads. To account for the variations in load and to maintain typical athletic training principles, the moderate and heavy loads were performed with a controlled eccentric phase and an explosive concentric phase whereas the light load was performed with a fast eccentric phase. The athletes were instructed not to jump in any of the loading conditions. Pre, mid and post-session maximal isometric voluntary contractions were also performed on a leg extension machine for each condition with the mid-test performed after the fifth set. In addition, each set was assessed via surface EMG. The researchers found that the heavy load session increased neuromuscular recruitment but failed to maintain power, indicating the accumulation of peripheral fatigue. In contrast, the medium load maintained neuromuscular recruitment but maintained power and produced less fatigue. The light load did not increase neuromuscular recruitment, maintained power and completely avoided any residual fatigue. These results show that different resistance training protocols produce different neuromuscular responses, indicating that the applied practitioner should utilise different protocols at different times within the yearly training cycle and weekly plan depending on goals. However, this study didn't provide any information on the time course of this fatigue, i.e. how long does it take for neuromuscular fatigue to return to pre-training levels. Additionally, whilst this study provided novel information regarding athlete responses to various resistance training protocols, the fatigue assessment tool used, isometric leg extension, whilst accurate, is not reflective of compound, multi-joint movements as seen in most athletic tasks. The study also does not indicate how these typical training protocols affect more common performance tests that may provide a more accurate indication of an athlete's readiness to perform dynamic, coordinated activities such as jumping and sprinting in either a training or competitive environment. More research needs to be performed to gain a greater insight in this area.

Limited research exists examining this particular area on maximum power training with only a study by Howatson et al. (2016) giving some indication to these acute responses. Elite track and field athletes performed either a maximum strength or power training session on separate days. Each session utilised three exercises, either a strength or corresponding power version, with the load during the power exercises equal to 30% of that used during the strength session. Four sets of five repetitions were performed with three minutes rest between sets. A maximal isometric knee extension test as used by Brandon et al. (2015) and three maximal CMJ's were assessed before, immediately post and 24 h post the training session. Differences between the two sessions showed that MVC of the knee extensors was found to be depressed immediately post and 24 h post the strength session but not following the power session which had no effect on MVC. This result reinforces the findings of Brandon et al. (2015), that heavy load, maximum strength training may lead to increased peripheral fatigue when compared to lower load, power training. No differences in CMJ were reported for either training group either mid-session, immediately post or 24 h post training indicating that the fatiguing effect of either resistance training session was not substantial enough to affect CMJ performance.

The above research shows that the acute neuromuscular effects of various resistance training protocols on training fatigue and post-training recovery dynamics can be assessed using EMG and isometric MVC tests. The type of acute effects seen may vary based on the type of training protocol used, the training age of the athlete and the training type of the athlete, i.e. strength/power based or endurance based. Additionally, it should be considered that the time-course of these effects may not be uniform and as such may require multiple assessment methods. Whilst the use of single joint, isometric measures to monitor this fatigue has been shown to be a useful laboratory based method, it's practical applications in the field is limited given it's time cost. The use of quicker and easier to administer performance tests that are commonly associated with athletic performance may provide useful global information in understanding the various neuromuscular effects of strength and power training and their effect on performance. Whilst limited research has investigated these effects in relation to strength and power training (Howatson et al., 2016) their practical applications remain unclear. This highlights the need for further research in this area as other studies have shown the usefulness of field based performance tests to assess neuromuscular fatigue such as the CMJ (Andersson, Raastad, Nilsson, Paulsen, Garthe, & Kadi, 2008; Cormack et al., 2008c), DJ (Byrne & Eston, 2002) and sprint tests (Gathercole et al., 2015a).

2.4 The effects of resistance training on adolescent athletes

The following section of this review focuses on the effects of resistance training on adolescents. Due to the studies in this thesis focussing on male athletes, this review will focus predominantly on male adolescents.

For the purpose of this review the term adolescent refers to the period of age between 14 – 18 y for males as has been used in previously (Behm et al., 2008; Faigenbaum et al., 2009). Whilst this is a common method to distinguish adolescence, it does come with limitations, namely the effect of contrasting maturity within a chronological age group (Malina et al., 2004; Sherar et al., 2007). This can lead to substantial differences among boys of different maturity status in physical tests of strength and power (Malina et al., 2004) and may have a subsequent effect on responses and adaptations to resistance training. A common method for assessing and controlling for biological age variation is the determination of years post peak height velocity (PHV), that is the age at which maximum growth rate occurs (Sherar et al., 2007).

The effects of resistance training on adolescence has been studied since the 1970's (Vrijens, 1978) and has continued to receive attention in the scientific literature. Over the past 15 years a growing interest in resistance training for children and adolescents has resulted in an increased number of studies focussed on these age groups (Behm et al., 2008; Behringer, Neuerburg, Matthews, & Mester, 2013;

Chelly et al., 2009; Christou et al., 2006; Croix, 2007; Drinkwater et al., 2005; Faigenbaum & McFarland, 2008; Faigenbaum, McFarland, Keiper, Tevlin, Ratamess, Kang, & Hoffman, 2007; Faigenbaum, Milliken, & Westcott, 2003; Faigenbaum, Ratamess, McFarland, Kaczmarek, Coraggio, Kang, & Hoffman, 2008; Faigenbaum & Schram, 2004; Faigenbaum, Westcott, Micheli, Outerbridge, Long, LaRosa-Loud, & Zaichkowsky, 1996b; Gorostiaga, Izquierdo, Iturralde, Ruesta, & Ibanez, 1999; Harries et al., 2016; Ingle, Sleap, & Tolfrey, 2006; Keiner, Sander, Wirth, Caruso, Immesberger, & Zawieja, 2013; Lillegard, Brown, Wilson, Henderson, & Lewis, 1997; Meylan, Cronin, Oliver, Hopkins, & Contreras, 2014; Philippaerts et al., 2006; Pikosky, Faigenbaum, Westcott, & Rodriguez, 2000; Pullinen et al., 2002; Pullinen et al., 1998; Ramsay, Blimkie, Smith, Garner, Macdougall, & Sale, 1990; Sailors & Berg, 1987; Sander, Keiner, Wirth, & Schmidtbleicher, 2013; Secomb, Nimphius, Farley, Lundgren, Tran, Parsonage, & Sheppard, 2015; Tibana, Prestes, da Cunha Nascimento, Martins, De Santana, & Balsamo, 2012; Tsolakis, Messinis, Stergioulas, & Dessypris, 2000; Tsolakis, Vagenas, & Dessypris, 2004). Further evidence of the interest in resistance training on these age groups can be found in the publication of position statements by various international strength and conditioning associations (Baker et al., 2011; Faigenbaum et al., 1996a; Lloyd et al., 2012), health organisations (Behm et al., 2008), an international consensus between leaders in related research (Baker et al., 2011; Lloyd et al., 2014), review articles (Behringer, Heede, Matthews, & Mester, 2011; Harries, Lubans, & Callister, 2012; Lesinski, Prieske, & Granacher, 2016; Malina, 2006; Moran, Sandercock, Ramírez-Campillo, Meylan, Collison, & Parry, 2016; Payne, Morrow Jr, Johnson, & Dalton, 1997) and discussion papers (Bernhardt et al., 2001; Guy & Micheli, 2001). In general, this body of work makes recommendations based on training for general children and youth populations with little guidance or specific recommendations for adolescent athletes who may be more advanced than their untrained peers (discussed in section 2.1). This increased exposure to resistance training may lead to an ability to tolerate and potentially require higher intensities of training to ensure adaptation to training does not stagnate. Behm et al. (2008) attempted to address this in the Canadian Society for Exercise Physiology position paper on resistance training in children and adolescents stating that, 'Youth with resistance training experience can gradually progress to more intense or voluminous workouts to target specific training objectives (i.e. strength, power, hypertrophy)', however the training guidelines they provided are not typical for the objectives mentioned and they provide no direct references justifying these guidelines. Lloyd et al. (2014), as part of an international consensus paper, extended these guidelines on the principle of physiological adaptation. This consensus statement suggested that adolescents who can display and maintain technical competency may utilise lower repetition ranges (≤6) and higher external loads (>85% 1RM) during periodic phases of strength training.

To accurately prescribe effective resistance training programs for adolescent athletes there must be a clear understanding of their specific physiological responses, recovery dynamics and adaptations to various programs such as maximum strength versus power training as exists for the adult population. An understanding of these responses, recovery, dynamics and adaptations will allow more specific guidelines to be developed for practitioners working with this growing subgroup of athletes. A portion of the current body of literature on this population group has focussed on the biochemical responses in relation to resistance training (Fry et al., 2000; Gorostiaga et al., 1999; Kraemer et al., 1992) and its comparison to adult responses. This has included both hormonal (testosterone, insulin-like growth factor and cortisol) and catecholamines (dopamine, adrenaline, noradrenaline). In comparing the results from these studies, substantial variation was seen in the results however it was apparent that differences exist between adolescents and adults in the biochemical responses to resistance training. One study directly compared the biochemical response of adolescent (14 ± 0 y) boys and male adults (27 ± 3 y) males to the same resistance training protocol (Pullinen et al., 2002). The subjects performed five sets of ten repetitions at 40% 1RM with 40 seconds rest between sets followed by two sets of maximal repetitions at the same intensity with three minutes rest between sets. Both the adolescents and adults performed a similar number of reps for their two max effort sets (adolescents 23 ± 9 and 18 ± 3; adults 21 ± 6 and 17 ± 7). A summary of these findings is presented in Table 2.4.

Table 2.4. A comparison of the biochemical response of adolescents and adults after performing a similar resistance training protocol (Pullinen et al., 2002)

Biochemical parameters		Adolescents	Adults
Hormonal (measured pre-exercise and post sub-max and max_2	Total testosterone	No Sig. changes	Sig. ↑ after max_2 only
	Free testosterone	No Sig. changes	Sig. ↑ after max_2 only
	Cortisol	Sig ↑ after max_2 only	No Sig. changes
Catecholamines (measured pre-exercise and post sub-max, max_1 and max_2)	Adrenaline	Sig. ↑ after max_1 and remained elevated after max_2	Sig. ↑ after max_1 and remained elevated after max_2
	Noradrenaline	Sig. ↑ after sub-max, further Sig, ↑ after max_1 and remained elevated after max_2	Sig. ↑ after sub-max, further Sig. ↑ after max_1 and Sig. ↑ after max_2

* Sig. = Significant; sub-max = sub-maximal sets, max_1 = 1st set of maximum repetitions, max_2 = 2nd set of maximum repetitions

The results of the study (Pullinen et al., 2002) showed that adolescent and adult males have different biochemical responses when exposed to the same resistance training stimulus. However, these findings cannot be extrapolated to maximum strength or maximum power training sessions as the exercise protocol used was not typical of 'normal' maximum strength or maximum power repetition/set schemes used in athletic training.

With the differences found in biochemical responses it could be reasonably assumed that differences also exist between these two age groups in morphological and neuromuscular responses. Previous research examining the effect of resistance training on morphological and neuromuscular responses and adaptations in adolescents is presented below. Due to the dearth of related research focussing on this population, no restriction was placed on the type of resistance training protocol (maximum strength, power, hypertrophy or other) used in these studies.

In a study by Gorostiaga et al. (1999) adolescent male handball players completed a six-week resistance training program to investigate neuromuscular adaptations in addition to their normal handball training. The resistance training group performed two resistance training sessions per week consisting of five exercises with four sets of varying repetitions performed whilst the handball group performed their normal handball training only. Intensities also varied across sets, beginning at 40% 1RM for the first two sets and increasing to 80% and 90% for the third and fourth sets respectively. As intensity increased, volume decreased, with the first two sets consisting of 12 repetitions whilst sets three and four had six and three repetitions, respectively. A rest period of approximately 1.5 minutes was given between sets. The authors found that the group who performed the strength training had a significant increase in maximal isometric force measured via unilateral leg extension and flexion while the control group showed no change. The resistance training group also had a significant increase in throwing velocity whilst the handball only group did not. In contrast, the handball group increased their squat jump height over the training period whilst the resistance training group had no change. The increases seen in the resistance training group are similar to results seen in adult athletes in response to resistance training. However the results from the jump squat are unexpected as the exercises utilised included half squats, a movement pattern that has been shown to have positive effects on jump height in adults (Rønnestad et al., 2012) although it must be considered that the exercise protocols used in both studies were substantially different.

In a similar study, young male soccer players (age = 13.8 ± 0.4 y) performed a 16 week resistance training program twice weekly (Christou et al., 2006). The players had 4.3 ± 1.9 y soccer playing experience however no mention was made of their resistance training history. It could be assumed they had no previous experience as the methods state that the strength training group performed a twice weekly, four-week introduction program at a reduced intensity. The study utilised three groups, a soccer training plus resistance training, a soccer training only and a control group were tested for 1RM leg press and bench press, SJ, CMJ, 30-m sprint time and peak sprint velocity. Whilst all three groups showed improvements in performance during the study, the resistance training group experienced greater improvements than the other groups. The results of the study suggest that the resistance training had a beneficial effect on performance although the average age of the participants was below that considered for adolescents. It must also be considered that the subjects possibly had no resistance training experience and as such, the results may not be representative of what could be expected in adolescent athletes with previous resistance training experience. Indeed, the resistance training protocol used for this study would suggest the untrained nature of the subjects as the set and repetition scheme progressed from two sets of 15 repetitions in week 1 to two sets of eight repetitions in week 16 with intensity starting at 55-60% 1RM and finishing at 75-80% 1RM.

In another study on adolescent (age = 17.0 ± 0.4 y) soccer players, Chelly et al. (2009) examined the effects, of a two month back half squat program performed twice weekly immediately before the regular season. The subjects performed four sets in the following regime; seven repetitions at 70% 1RM, four repetitions at 80% 1RM, three repetitions at 85% 1RM and two repetitions at 90% 1RM with 1RM reassessed after week four of the training. To assess changes in performance both the strength and control group performed pre-post testing of SJ, CMJ, 5-jump test, 40-m sprint, cycle ergometer power test and anthropometry assessment to calculate thigh CSA. The strength group experienced a larger change in performance in SJ height, 5-jump distance, cycling power and various running velocity measures. Whilst this appears to be a beneficial finding at first glance, it should be noted that none of the subjects had previous resistance training experience. This could significantly affect the adaptations shown by the resistance training group who, although termed 'athletes', were novices with regards to resistance training.

Drinkwater et al. (2005) examined the acute fatigue response and adaptations of two types of resistance training protocols in elite junior basketball (age = 18.6 ± 0.3 y) and soccer (age = 17.4 ± 0.5 y) players. All subjects had previous resistance training experience ranging between six months to three years and were pair-matched for sport, strength and years of experience and were placed into either a repetitions failure or repetitions not to failure group. The repetitions failure protocol consisted of eight sets of three repetitions whilst the not to failure protocol consisted of four sets of six repetitions with the goal of either protocol to either allow the subject to perform all reps during the training session or to require a spotter to help the subject complete the final reps of their training program. Training was performed three times per week on the bench press with exercise intensity ranging from 85-105% 1RM across a six-week training period. Results of the training showed that whilst both groups experienced an increase in bench throw power, the repetitions to failure group experienced a greater increase than the non-failure group. This study shows the neuromuscular benefits of maximal strength training in adolescent athletes, although the age of the subjects was at the very limit of and some cases exceeding what is considered adolescent (14-18 y).

Pullinen et al. (2002) compared the effects of resistance training on isometric and MVC in adolescent versus adult athletes . Adolescent (14.0 ± 0 y) males and adult (27.0 ± 3.0 y) males performed an isometric MVC of the knee extensor muscles before and after seven sets of dynamic bilateral knee extension flexion movements. The exercise regime was performed in two parts: Part 1 required the subjects to perform five sets of 10 repetitions at 40% of 1RM with 40 s recovery between sets and three minutes later perform Part 2, comprising two sets of maximal repetitions with the same load with three minutes recovery between sets. Both the adolescent and adults showed significant peripheral neuromuscular fatigue with a decrease in MVC post the exercise session however no difference in the changes was observed between groups. These results suggest that adolescent and adult subjects had a similar fatigue response to the training protocol. The implications of this to the applied practitioner in athletic development however are limited given the non-traditional resistance training protocol used was substantially different from that found in typical maximum strength or power training protocols.

In a study on adolescent surfers, Secomb et al. (2015) examined the effects of a twice weekly strength training program performed for seven weeks on a battery of tests. The performance tests consisted of the CMJ, SJ and IMTP whilst lower body muscle structure was assessed via ultrasonography of the vastus lateralis (VL) and lateral gastrocnemius (LG) for thickness, pennation angle and fascicle length. Minimal detail was provided on the make-up of the strength training sessions, simply being referred to as consisting of 'both upper- and lower-body compound movements, that were appropriately block periodised'. Results from the study show that no effects from the strength training program were seen on any of the performance tests. Additionally, the only morphological test to show change post-training was an increase in VL thickness. Interestingly, the study included a follow up test session three weeks after the cessation of strength training. A performance improvement was noted in IMTP peak force and relative peak force, relative to the pre-testing, however not when compared with the post testing session. The authors concluded that adolescent athletes may require a longer time period to realise strength gains from a program than can be seen in testing immediately post a training block. Interestingly, a performance decrement was seen in SJ peak velocity when compared with the post-training testing as well as decreases in VL fascicle length and VL thickness. This may indicate that the performance improvements seen in the IMTP were related to improved familiarity with the test rather than actual performance changes given that underpinning morphological changes were in direct contrast to these results.

The studies listed above have examined adaptations across a moderate training time frame (6-16 weeks). However, in a substantially longer study, Sander et al. (2013) examined the effects of a two-year resistance training program on back and front squat 1RM and 30 m sprint in youth soccer players. A large cohort of athletes (n=134) were split across three groups according to age at pre-test with an under 19 group (A), under 17 group (B) and an under 15 group (C) with each group divided in half again to provide an experimental group and a control group. Due to U-19 and U-15 groups both having athletes outside of the adolescence age guidelines listed above, their results will not be discussed. Following the two-year training period, U-17 strength trained athletes showed significant improvements in 30-m sprint time at the 5-, 10-, 20- and 25-m splits. Additionally, the strength group showed a significantly higher increase in back and front squat 1RM strength after the two-year training period. It is interesting to note that the percentage increase in performance seen in the back and front squat for the strength group was 115% and 123% respectively, whilst the range of performance increase seen across the 30-m splits was (-3.8% to -4.6%) indicating the transference of strength improvements to sprint speed improvements was limited and reinforcing the concept of specificity of training as discussed previously. In another study examining youth soccer players (age = 17 ± 0.5 y), subjects performed a strength training program twice weekly for two months. To assess changes in performance, pre- and post-testing was performed on the SJ, CMJ and 40-m sprint. Additionally, morphological changes were assessed via changes in leg muscle volume, thigh muscle volume and mean thigh CSA. A typical maximum strength training protocol was used with training loads of 85% 1RM or above used throughout the two-month training block with back half squat utilised as a training exercise. No significant changes were observed in any of the morphological tests. Conversely, 40-m sprint and SJ significantly improved when compared with changes in the control group. The improvements in neuromuscular measures and lack of change in morphological variables compares favourably with the effects of maximum strength training seen in adults.

The studies reviewed above highlights the variations in responses to strength training in adolescent athletes. Nevertheless, the limitations of using novice resistance trained athletes and various 'non-traditional' strength/power protocols highlight the need for further applied research using more traditional strength/power training programs with resistance trained adolescent athletes. Additionally, to the author's knowledge, no research exists highlighting the acute neuromuscular fatigue responses to strength training over an extended period (48 h) as found in adult literature (Howatson et al., 2016; McCaulley et al., 2009). This information could prove critical in better understanding adolescent athlete recovery time courses and thus provide crucial information regarding structuring weekly training.

2.5 Performance tests as a measurement tool for neuromuscular fatigue

Performance tests are now commonly used to assess neuromuscular fatigue in various sports and exercise modalities (Andersson et al., 2008; Cormack, Newton, McGuigan, & Cormie, 2008a; Gathercole et al., 2015b; Johnston et al., 2016; Ronglan et al., 2006; Wiewelhove et al., 2015). The benefits of using these tests to monitor neuromuscular fatigue is that they provide a valid, reliable test that requires minimal familiarisation and produces minimal fatigue, thus limiting their impact on sport-specific training or competition (Gathercole et al., 2015a).

In assessing neuromuscular fatigue following a fatiguing Yo-Yo running protocol, Gathercole et al. (2015a) found the CMJ to be superior to the DJ and squat jump (SJ) based on the number of variables, the size of the effects and the time course (immediate and prolonged). However, the DJ also showed substantial effects and the 20-m sprint showed the largest decrease immediately post the fatiguing protocol however recovered within 24 h. This research also introduced a novel analysis method to assess fatigue, adding technique related variables such as concentric and eccentric time, based off previous work by Cormack et al. (2008b). Gathercole et al. (2015a) reported that the use of both output (jump height, peak power) and technique variables strengthened the diagnosis of neuromuscular fatigue and further expanded upon this in subsequent research examining neuromuscular fatigue in snow-boarding athletes (Gathercole et al., 2015b). Given the common acceptance of performance tests in assessing acute neuromuscular fatigue it could be hypothesised that these tests would also be a practical diagnostic tool for examining the effects of various resistance training protocols on neuromuscular fatigue.

The research presented above confirms that various resistance training protocols elicit different neuromuscular responses. However, more research is needed to explore the effect of these different training methods on performance tests. A greater understanding of these acute responses may lead to more appropriately structured resistance training programs that in turn can drive greater chronic physiological adaptations.

2.6 Monitoring athlete performance and readiness

This review so far has detailed the acute physiological responses and adaptations of adult athletes to maximum strength and power training programs. However, resistance training entails only a part of the weekly training schedule that is used in the development of athletes for elite sport. Other training modalities include conditioning, speed and agility and the sport specific technical/tactical training required for their chosen sport (Mendez-Villanueva, Buchheit, Kuitunen, Douglas, Peltola, & Bourdon, 2011; Millet, Candau, Fattori, Bignet, & Varray, 2003; Siegler, Gaskill, & Ruby, 2003). During the annual training cycle, coaches will manipulate the volume and intensity of these training modalities based on the goal of the current training plan and their place within the preparation or competitive season. To track the longitudinal athletic performance changes of an athlete, regular monitoring may be performed utilising tests to assess the different physiological systems being developed. In addition, it is also important to understand an athlete's current level of preparedness, which has been described previously as the athletes level of fitness minus any fatigue that exists from acute or chronic training load (Chiu & Barnes, 2003; Zatsiorsky & Kraemer, 2006). This concept can also be applied to a single training session, as depicted in Figure 2.3 with the positive 'fitness' effects generated by a workout summed with the negative 'fatigue' effects generated by the same workout to give the athletes level of preparedness.

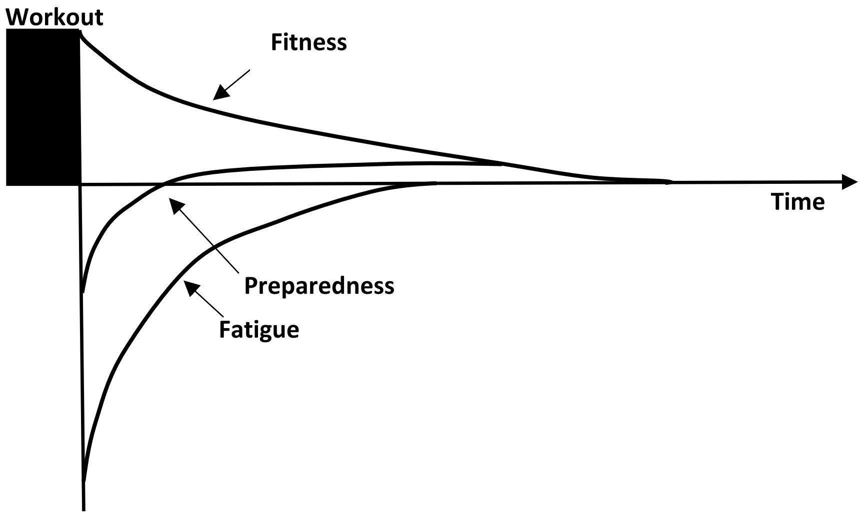


Figure 2.3. The fitness-fatigue model also known as the two-factor theory. Adapted from Zatsiorsky & Kraemer, 2006

To assess an athlete's current level of preparedness, numerous monitoring tools have been developed. These monitoring tools are generally grouped as either a neuromuscular type (Cormack et al., 2008c; Twist & Highton, 2013), cardiac parasympathetic activity (Stanley, D'Auria, & Buchheit, 2015), biochemical (Coutts, Reaburn, Piva, & Rowsell, 2007; Twist & Highton, 2013) or athlete self-report measures (Foster et al., 2001; Twist & Highton, 2013). Neuromuscular monitoring is now common place, with practitioners utilising a range of tests across both adult and adolescent athletes. In adults these tests include the SJ (Argus, Gill, Keogh, McGuigan, & Hopkins, 2012; Gee, Caplan, Gibbon, Howatson, & Thompson, 2016), CMJ (Andersson et al., 2008; Johnston et al., 2016; Spiteri, Nimphius, Wolski, & Bird, 2013), DJ (Byrne & Eston, 2002), IMTP (Beattie et al., 2016; Kawamori et al., 2006) and short sprints (Baker & Newton, 2008; Fletcher & Jones, 2004; Wiewelhove et al., 2015) whilst similarly in adolescent athletes research has also utilised the SJ (Chelly et al., 2009; Coelho E Silva, Figueiredo, Moreira Carvalho, & Malina, 2008), CMJ (Christou et al., 2006; Santos & Janeira, 2008), DJ (Foden, Astley, Comfort, McMahon, Matthews, & Jones, 2015), IMTP (Secomb et al., 2015) and sprint (Dasteridis, Piliandis, & Mantzouranis, 2011; Sander et al., 2013) performance monitoring tests.

The popularity of neuromuscular tests is due to several reasons including (Twist & Highton, 2013):

- Their ability to monitor low-frequency fatigue compared with other indirect markers.
- Ease of administration.
- Non-invasive.
- Reliability

As a result of these properties and their links with the neuromuscular responses/adaptations seen after resistance training, neuromuscular tests should be considered as an appropriate way to monitor longitudinal performance and acute preparedness in elite athletes.

2.6.1 Reliability and validity of neuromuscular monitoring tests

With any test or monitoring tool, the reliability of the test must be high to allow the practitioner confidence that any change shown in test performance is a 'real' change associated with a change in the performance of the individual performing the test and not the sum of any measurement errors. Such errors include the biological variation between tests and the error of measurement associated with the test based on the tester and/or equipment used (Hopkins, 2000a). Additionally, the validity of neuromuscular tests is an important consideration when considering their use.

Whilst multiple sub-qualities of validity exist (Johnson, 1997), it's importance in performance testing relates to how closely a test replicates results when compared against a criterion reference test of similar type and is referred to as concurrent validity (Aragón, 2000; Leard, Cirillo, Katsnelson, Kimiatek, Miller, Trebincevic, & Garbalosa, 2007). For example, is vertical jump height as measured by a Vertec valid against a criterion measure of jump height assessed using a three camera motion analysis system (Leard et al., 2007). Previous research has examined validity in common neuromuscular tests used (Aragón, 2000; James, Roberts, Haff, Kelly, & Beckman, 2017). However, more research is required to ensure that criterion measures exist for the range of tests available and their associated variables. Given the expanding use of various neuromuscular tests in performance assessment and fatigue monitoring, additional research should be performed to determine the validity of each test for the assessment method it is being chosen for.

The reliability of the neuromuscular tests outlined above has received significant focus in the literature with a number of variables within each test being noted as acceptable in adults (i.e. coefficient of variation (CV) <10%) (Cormack et al., 2008b) (Alemany, Pandorf, Montain, Castellani, Tuckow, & Nindl, 2005; Aragón, 2000; Cormack et al., 2008b; Duthie, Pyne, Ross, Livingstone, & Hooper, 2006; Feldmann, Weiss, Ferreira, Schilling, & Hammond, 2011; Flanagan, Ebben, & Jensen, 2008; Hori, Newton, Kawamori, McGuigan, Kraemer, & Nosaka, 2009; Kurz, Lang, Richter, & Schwameder, 2009; Lloyd, Oliver, Hughes, & Williams, 2009; Moir, Button, Glaister, & Stone, 2004; Moir, Garcia, & Dwyer, 2009; Slinde, Suber, Suber, Edwen, & Svantesson, 2008; Taylor, Cronin, Gill, Chapman, & Sheppard, 2010). This literature confirms that the CMJ, DJ, IMTP and short sprints all contain specific variables that can be considered reliable if the assessor, test equipment, protocol and time of day are controlled for.

Whilst the reliability of these tests has been proven to be acceptable when used to assess adult athletes and despite their common place use with adolescent athletes, very little scientific research exists examining whether the same levels of reliability apply when used to assess changes in adolescent athlete performance or preparedness. As such, this leaves a gap in the scientific literature which requires attention. One study that contributes to this area of interest examined the between day reliability of CMJ performance amongst other markers in adolescent rugby union players (Roe, Darrall-Jones, Till, Phibbs, Read, Weakley, & Jones, 2016). The authors reported that between day (5 days) reliability of multiple variables were acceptable compared to the value above (CV < 10%). The authors also noted the need for reliability data to be population specific based on factors such as physical characteristics and anthropometry. This reinforces the need for subsequent reliability research into neuromuscular tests that are used in various adolescent athletes.

Chapter 3

Reliability of common neuromuscular performance tests in adolescent athletes

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This chapter was designed to assess the reliability of neuromuscular tests commonly used in the assessment of athletes' during their annual training cycle. Whilst previous research has determined the reliability of the CMJ, DJ, IMTP and 20-m sprint in adult athletes, no data exists confirming the reliability of these tests in an adolescent athlete population. Prior to these tests being used to assess changes in performance over a training block or as a measure of acute neuromuscular readiness, their reliability must be determined.

3.1 Abstract

The purpose of this study was to examine the reliability of four commonly used neuromuscular tests and their associated variables in adolescent athletes. A total of 17 male adolescent athletes (age 16.5 ± 1.1 y, height 171.2 ± 6.3 cm, body mass 65.5 ± 11.2 kg) performed a test battery consisting of the countermovement jump (CMJ), drop jump (DJ), isometric mid-thigh pull (IMTP), all performed on a force plate and 20-m sprint on two consecutive days. Inter-day reliability of a number of variables from each test was determined using the coefficient of variation (CV) and intraclass correlation coefficient. A number of variables within each test were found to have acceptable inter-day reliability (CV < 10%) with corresponding reliable ICC values greater than 0.75. For the CMJ and DJ peak concentric impulse (CV = 1.6%; ICC = 0.99 and 5.1%; 0.94 respectively) and take-off velocity (CV = 1.7%; ICC = 0.97 and 4.8%; 0.85 respectively) were the most reliable variables. Other commonly reported variables also showed acceptable levels of reliability for both tests such as peak power (CV = 3.2%; ICC = 0.98 and 6.1%; 0.95) and jump height (CV = 3.4%; ICC = 0.96 and 9.8%; 0.85, respectively). Peak force was the most reliable variable in the IMTP (CV = 6.4%; ICC = 0.87) as was the 20-m split time for the 20-

m sprint (CV = 0.8%; ICC = 0.98). Peak RFD was not found to be reliable in any of the tests it was measured (CMJ, DJ and IMTP). The results of this study indicate that the CMJ, DJ, IMTP, 20-m sprint are reliable measures of performance in adolescent athletes.

3.2 Introduction

Athletic preparation, specifically the development of strength and power characteristics, can be monitored by a number of different performance tests (Cormie et al., 2010; Newton, Rogers, Volek, Hakkinen, & Kraemer, 2006; Stone et al., 2003). The countermovement jump (CMJ), drop jump (DJ), isometric mid-thigh pull (IMTP) and various sprint tests are all commonly used to quantify changes in athletic performance (Cormie et al., 2010; McGuigan & Winchester, 2008; McGuigan et al., 2006; Stone et al., 2003; Stone, Sands, Pierce, Carlock, Cardinale, & Newton, 2005; Viitasalo et al., 1998). In order to ensure that the changes being reported from test to test are indeed a real change in athletic capabilities and not the technical error of measurement or 'noise' present within a test it is essential each test used be reliable (Cormack et al., 2008b; Duthie et al., 2006; Moir et al., 2004). Common measures of reliability are the CV and intraclass correlation coefficient ICC. The CV refers to 'the typical percent error', the standard deviation of an individual's repeated measures expressed as a percent of the individual's mean test score and is the within subject random variation from one trial to the next (Hopkins, Schabort, & Hawley, 2001). The ICC, measures how well the values from one trial relate to the values from another trial when moving from subject to subject as well as the reproducibility of the rank order of the subjects on retest (Hopkins, 2000a; Hopkins et al., 2001).

Numerous reliability studies have been performed on the aforementioned tests in adult populations (Aragón, 2000; Cormack et al., 2008b; Feldmann et al., 2011; Flanagan et al., 2008; Hori et al., 2009; Kurz et al., 2009; Randell, Cronin, Keogh, Gill, & Pedersen, 2011) with previous researchers stating that a CV of less than 10% can be classed as reliable (Cormack et al., 2008b). Although there is differing opinion in the literature, an ICC of > 0.75 has previously been described as reliable in neuromuscular tests (Walmsley & Amell, 1996). These studies have reported on the reliability of certain variables that can be extracted from these tests and have established a practical range of CV's and ICC's that can be expected from performing these tests with an adult population using a variety of measurement devices and protocols. Reliability of CMJ variables has been shown to range from a CV of 1.0% - 36.3% (Cormack et al., 2008b; Moir et al., 2004; Sheppard et al., 2008a) with ICC's of 0.25-0.96 (Sheppard et al., 2008a). In a study by Cormack et al., (2008b) the authors found that mean force was the most reliable variable (CV = 1.1%), with flight time (CV = 2.9%), peak force (CV = 3.5%) and peak power (CV = 3.5%) also showing excellent reliability whilst concentric time (CV = 17.1%) and concentric:

eccentric time (CV = 16.5%) showed unacceptable levels of reliability. Sheppard et al., (2008a) found similar results for peak force in the CMJ (CV = 3.5%; ICC = 0.96) however peak power (CV = 9.5%; ICC = 0.80), whilst still reliable was not as strong. The authors also reported that rate of force development (RFD), a commonly reported variable, was highly unreliable (CV = 36.3%; ICC = 0.43).

Drop jump variables have also been shown to be reliable with CV's ranging from 6.1% - 11.3% with ICC's of 0.83-0.94 (Feldmann et al., 2011). Feldman and colleagues (2011) reported jump height (CV = 6.1%; ICC = 0.94) and contact time (CV = 8.2; ICC = 0.83) as reliable whilst reactive strength index (RSI)(CV = 11.3%; ICC = 0.94) though reported as reliable by the authors failed to meet the criterion for CV reliability detailed.

In relation to the IMTP, previous research has shown the CV of various variables to range from 2.3% (peak force) to 10.1% (RFD) (McGuigan, Newton, & Winchester, 2008). Other researchers have reported the ICC's for specific IMTP variables ranging from 0.81 for peak RFD to 0.98 for peak force (McGuigan & Winchester, 2008; Stone et al., 2003). Reliability data surrounding the 20-m sprint and associated variables has also been shown to have excellent reliability with Fletcher & Jones (Fletcher & Jones, 2004) showing 20-m sprint time had a CV of 1.7% with an associated ICC of 0.94. Additionally, Tanner reported a CV of 2.9% for 20-m sprint time (2012).

Whilst there are a number of studies on athletic adult population groups as mentioned above, limited data exists on the reliability of these tests when performed on an athletic, adolescent population group. Whilst some studies exist that have utilised some of these or similar performance tests in non-athletic (Nuzzo, Cavill, Triplett, & McBride, 2009) and athletic (Kurz et al., 2009; Quatman, Ford, Myer, & Hewett, 2006) adolescent population groups, to the authors knowledge, there is no research to date that has directly investigated the reliability of all these neuromuscular tests simultaneously within one athletic population group. As such, it is unknown whether these tests remain reliable given the inclusion of the increased physical development that occurs during adolescence and its consequent effect on anthropometric variables such as limb length, and lean body mass.

Therefore, the purpose of this study was to investigate the inter-day reliability of the CMJ, DJ, IMTP and 20-m sprint across a range of parameters in an athletic adolescent population.

3.3 Methods

Approach to the Problem

To assess the inter-day reliability of various parameters taken from four neuromuscular tests commonly used to measure athletic performance, a group of adolescent athletes performed three trials each of CMJ's, 20-m sprints and DJ's and two IMTP trials separated by 24 hours. This test-retest period was chosen to provide reliability data for the forthcoming study examining acute changes in these performance tests at 24-hour time periods (Chapter 5). In an attempt to standardise testing days, both test sessions were performed immediately after the weekend, during which no training took place. Prior to the first testing session a 4-wk familiarisation block was utilised for the tests subjects were not familiar with, specifically the IMTP and Drop Jump. Due to equipment constraints, familiarisation was limited to correct technique execution of the tests as no force plates were available to give performance feedback on either test.

Participants

Seventeen male adolescent athletes (age 16.5 ± 1.1 y, height 171.2 ± 6.3 cm, body mass 65.5 ± 11.2 kg, back squat 3RM = 82.6 ± 23.7 kg) who were students at an elite sports academy participated in the test-retest reliability study. The students competed in a range of sports including Squash, Fencing and Judo and each participant had a minimum background of two years of resistance training and was familiar with all of the tests used. As part of their normal training week, each participant performed eight training sessions including both physical preparation and sports specific training. All participants received a clear explanation of the study, including the risks and benefits of participation and were asked to provide their written consent before the start of the study. The study was approved by the Institutional Human Research Ethics Committee.

Procedures

At the beginning of each test session participants were required to complete a standardised 10 minute dynamic warm-up which included dynamic running drills, dynamic stretches, CMJ's, DJ's and 25-m submaximal sprints. In addition to the warm-up, practice trials for the CMJ, DJ and 20-m sprint were performed before testing began. The practice trials consisted of 2 sets of 3 at 80-90% effort for the CMJ, 1 set of 3 DJ performed from a 30cm box and 1 20-m sprint performed at 90% effort. Two submaximal IMTP practice trials were performed immediately prior to the IMTP testing effort. Upon completion of the warm-up, the participants performed the four neuromuscular tests in the same order, that is, 3 trials each of CMJ's, 20-m sprints, DJ's from a 40 cm box and 2 trials of an IMTP. To assist with controlling technical and biological variations across the two days, equipment was calibrated prior to use, tests were performed at the same time of day and participants wore the same shoes for each testing session. Participants were given a minimum of two minutes rest when moving from one test type to the next.

Countermovement Jump

Participants were required to perform the CMJ with their hands placed on their hips for the entire trial as has been used in previous research (Cormack et al., 2008b). All jumps were performed on a, permanently mounted force plate (9287BA Kistler Force Plate, Kistler Instrument Corp, Winterthur, Switzerland). Countermovement depth was self-selected with the participant instructed to utilise a technique that would result in the maximum height possible. A minimum of 1 minute rest was provided between each effort.

20-metre sprint

The 20-m sprints were performed on an indoor running track using dual-beam electronic timing gates (Swift Performance Equipment, Lismore, Australia). A staggered starting stance was chosen with the participant self-selecting which foot to place in front. When the participant was given the command 'ready' they began the maximal effort sprint at a self-selected time, thus eliminating reaction time. Splits were measured at 5, 10 and 20-m. Foot movement or swaying of the upper-body to facilitate momentum was not allowed. A minimum of 2 minutes rest was given between trials with participants performing three valid trials.

Drop Jump

The DJ's were performed on two force plates (9287BA Kistler Force Plate, Kistler Instrument Corp, Winterthur, Switzerland) with the participant beginning on a 40-cm box placed on the first force plate and performing the drop jump on to an adjacent force plate. When instructed, the participant stepped off the box towards the force plate attempting to minimise vertical displacement. The participants were instructed to minimise ground contact time whilst attempting to maximise height as has been used in previous research (Hamilton, 2009a). As per the CMJ, participants were required to perform the trial with their hands placed on their hips with a minimum rest of 1 minute given between efforts.

Isometric mid-thigh pull

The IMTP was conducted on a portable force plate (9281CA Kistler Force Plate, Kistler Instrument Corp, Winterthur, Switzerland) with each participant having previously determined the appropriate height of the bar to perform the trials. This was determined by the following protocol. The participant starting position consisted of the mid-line of the foot being placed directly under the bar, the bar height was set to the first adjustable position above the top of the patella, shoulders were set forward of the bar, a pronated hook grip was used to hold the bar with arms straight and a neutral or slightly lordotic spine position. The bar was adjustable in 3cm increments resulting in a knee angle of between 145–150 degrees in every participant. Following a warm-up consisting of two sub-maximal trials, participants assumed the starting position where they were instructed to 'take tension' by beginning to apply a minimal amount of force through their feet before maximally pulling on the bar by attempting to drive their feet through the ground. Subjects were not required to pull as fast as possible, rather they were instructed to build force to a maximal effort and maintain for an effort of 5 seconds. A trial was deemed as a failure if the foot position was unable to be maintained, shoulders did not remain in front of the bar, the arms bent during the trial, excessive kyphosis or lordosis occurred, knee angle was not maintained in which case it was discarded and another trial performed. The testing session was concluded after the completion of 2 successful trials.

All trials from the CMJ's, DJs and IMTP's were collected at a sample rate of 500 Hz and were analysed using custom-designed software using the impulse momentum approach as described previously (Dugan, Doyle, Humphries, Hasson, & Newton, 2004). The raw data from the force plate was filtered and smoothed using a fourth-order, low-pass Butterworth digital filter with a cut-off frequency of 10 Hz.

Statistical Analyses

The mean ± standard deviation was calculated for all variables within each neuromuscular test. Additionally, the change in means from trial one to trial two was calculated as a percent change with 90% confidence limits. The inter-day reliability of each test was determined by calculation of the coefficient of variation (CV) and intraclass correlation coefficient (ICC) with 90% confidence limits for the best of 3 trials for the CMJ, DJ and 20-m sprint and best of 2 trials for the IMTP. Both the CV and ICC for the four neuromuscular tests were calculated utilising the Hopkins Excel spreadsheet (Hopkins, 2000b). A variable was deemed as reliable if the CV was less than the threshold of 10% as has been used in previous literature (Cormack et al., 2008b). In conjunction with this, an ICC threshold of 0.75 has previously been used as a threshold for reliable data and therefore was subsequently used in the current study (Randell et al., 2011). A Pearson correlation was also used to determine the relationship between all variables. The magnitude of relation was reported based on the following thresholds; nearly perfect (>0.90), very high (0.9 – 0.7) and high (0.7 – 0.5) as proposed by Hopkins (Hopkins, Marshall, Batterham, & Hanin, 2009).

3.4 Results

Inter-day (1 day) reliability for the variables measured from the four neuromuscular performance tests for the best of three trials are shown in Tables 3.1–3.3. Variables that had a CV < 10% and are commonly used are presented. Selected variables that are commonly examined in these performance tests but resulted in a CV of greater than 10%, a level referred to as unreliable in previous literature (Cormack et al., 2008b), were also included.

Within the CMJ (Table 3.1) the most reliable variables were peak concentric impulse (CV = 1.6%, ICC = 0.99) and take-off velocity (CV = 1.7%, ICC = 0.97). Other variables that displayed excellent reliability were peak power (CV = 3.2%, ICC = 0.98), relative peak power (CV = 3.4%, ICC = 0.91) and jump height from force (CV = 3.4%, ICC 0.96). Peak rate of force development (RFD) displayed unacceptable reliability (CV = 37.8%, ICC = 0.27).

Within the DJ take-off velocity was the most reliable variable followed closely by a number of other variables such as peak concentric impulse, mean concentric power and peak concentric power (Table 3.2). A number of commonly reported variables displayed unacceptable levels of reliability including contact time, peak force and peak RFD.

The IMTP (Table 3.3) was analysed across three variables with peak force (CV = 6.4%, ICC = 0.87) and relative peak force (CV = 6.4%, ICC = 0.73) both displaying acceptable levels of reliability whereas peak RFD did not (CV = 26.1%, ICC = 0.64).

The 20-m sprint (Table 3.3) displayed excellent reliability across all variables measured ranging from 20-m split (CV = 0.8%, ICC = 0.98) as the most reliable variable to 10-20-m split (CV = 2.7%, ICC = 0.80) as the least reliable variable.

Correlations between selected variables from the four performance tests are presented in Table 3.4. Nearly perfect correlations ($r > 0.90$) were observed between variables within a performance test for CMJ, DJ and 20-m sprint and between tests for CMJ peak concentric impulse and DJ peak concentric impulse ($r = 0.92$) and also between CMJ peak power and DJ peak concentric impulse.

Table 3.1. Countermovement jump inter-day reliability variables

Variable	Mean ± SD	Change in Mean (%)	CV (%)	ICC
Peak concentric impulse (N.s)	196.0 ± 44.5	-0.5 (-1.5 to 0.5)	1.6 (1.3 to 2.1)	0.99 (0.99 to 1.00)
Take-off velocity ($m.s^{-1}$)	2.75 ± 0.26	-0.4 (-1.4 to 0.5)	1.7 (1.3 to 2.4)	0.97 (0.92 to 0.99)
Peak power (W)	3677 ± 831	-1.8 (-3.6 to 0.1)	3.2 (2.5 to 4.6)	0.98 (0.95 to 0.99)
Relative peak power ($W.kg^{-1}$)	54.2 ± 6.0	-1.9 (-3.8 to 0.1)	3.4 (2.6 to 4.9)	0.91(0.80 to 0.96)
Jump height from force (m)	0.42 ± 0.08	-0.8 (-2.7 to 1.2)	3.4 (2.7 to 4.9)	0.96 (0.91 to 0.98)
Peak concentric force (N)	1694 ± 321	-3.9 (-6.8 to -0.8)	5.4 (4.2 to 7.7)	0.92 (0.81 to 0.97)
Concentric phase duration (s)	0.27 ± 0.04	5.5 (1.8 to 9.5)	6.3 (4.9 to 9.0)	0.76 (0.50 to 0.89)
Centre of gravity downwards movement (m)	0.35 ± 0.08	6.2 (1.9 to 10.7)	7.2 (5.6 to 10.3)	0.89 (0.75 to 0.95)
Ratio eccentric/concentric duration (%)	221 ± 38	0.9 (-3.4 to 5.4)	7.6 (5.8 to 10.9)	0.76 (0.51 to 0.89)
Eccentric phase duration (s)	0.59 ± 0.08	6.5 (1.7 to 11.5)	8 (6.2 to 11.5)	0.7 (0.40 to 0.86)
Peak RFD ($kN.s^{-1}$)	11.98 ± 6.93	-11.1 (-26.6 to 7.8)	37.8 (28.4 to 57.6)	0.27 (-0.15 to 0.62)

* ± 90% CL are displayed for change in mean, CV and ICC in the brackets.

Table 3.2. 40 cm drop jump inter-day reliability variables

Variable	Mean ± SD	Change in Mean (%)	CV (%)	ICC
Take-off velocity ($m.s^{-1}$)	2.31 ± 0.29	2.1 (-0.7 to 5.0)	4.8 (3.7 to 6.8)	0.85 (0.67 to 0.94)
Peak concentric impulse (N.s)	159.2 ± 37.3	2.3 (-0.7 to 5.3)	5.1 (3.9 to 7.3)	0.94 (0.87 to 0.98)
Ratio eccentric/concentric duration (%)	106 ± 14	1.5 (-1.9 to 5.0)	5.8 (4.5 to 8.3)	0.85 (0.66 to 0.93)
Mean concentric power (W)	2414 ± 709	1.2 (-2.3 to 4.7)	5.9 (4.6 to 8.5)	0.95 (0.89 to 0.98)
Peak concentric power (W)	4305 ± 1325	-0.1 (-5.1 to 5.1)	6.1 (4.7 to 8.8)	0.95 (0.89 to 0.98)
Peak relative concentric power (W)	63.4 ± 14.5	0.7 (-3.0 to 4.5)	6.4 (5.0 to 9.2)	0.92 (0.82 to 0.97)
Reactive Strength Index ($m.s^{-1}$)	1.28 ± 0.39	1.4 (-3.9 to 7.0)	9.4 (7.3 to 13.6)	0.92 (0.81 to 0.96)
Jumping Height from force (m)	0.28 ± 0.07	4.2 (-1.5 to 10.2)	9.8 (7.6 to 14.2)	0.85 (0.67 to 0.94)
Peak RFD ($kN.s^{-1}$)	13.28 ± 6.67	1.5 (-13.6 to 19.4)	31.1 (23.5 to 46.7)	0.62 (0.28 to 0.83)

Reactive strength index = jump height from force / contact time; ± 90% CL are displayed for change in mean, CV and ICC in the brackets.

Table 3.3. Isometric mid-thigh pull and 20-m sprint inter-day reliability variables

Variable	Mean ± SD	Change in Mean (%)	CV%	ICC
20-m sprint times				
20-metre split (s)	3.18 ± 0.17	-0.6 (-1.1 to -0.1)	0.8 (0.6 to 1.1)	0.98 (0.95 to 0.99)
10-metre split (s)	1.85 ± 0.11	0.1 (-0.6 to 0.8)	1.2 (0.9 to 1.7)	0.96 (0.91 to 0.98)
5-10-metre split (s)	0.74 ± 0.04	0.5 (-0.7 to 1.8)	2.1 (1.6 to 3.1)	0.85 (0.66 to 0.93)
5-metre split (s)	1.10 ± 0.08	-0.6 (-1.9 to 0.6)	2.1 (1.7 to 3.0)	0.92 (0.81 to 0.96)
10-20-metre split (s)	1.31 ± 0.07	-1.3 (-2.8 to 0.3)	2.7 (2.1 to 3.8)	0.8 (0.57 to 0.91)
Isometric mid-thigh pull				
Peak force (N)	2176 ± 375	5.8 (1.8 to 9.9)	6.4 (4.9 to 9.4)	0.87 (0.71 to 0.95)
Relative peak force (BW)	3.35 ± 0.41	5.7 (1.7 to 9.9)	6.4 (5.0 to 9.4	0.73 (0.45 to 0.88)
Peak RFD ($kN.s^{-1}$)	9.4 ± 3.5	-10.1 (-22.1 to 3.8)	26.1 (19.7 to 39.6)	0.64 (0.29 to 0.84)

Body weight (BW), Rate of force development (RFD), ± 90% CL are displayed for change in mean, CV and ICC in the brackets.

Table 3.4. Correlations between neuromuscular test variables

		Countermovement jump						Drop jump					20-m sprint			Isometric mid-thigh pull	
		Peak concentric impulse (Ns^{-1})	Take off velocity (ms^{-1})	Peak power (W)	Peak relative power ($W.kg^{-1}$)	Jump height (m)	Peak concentric force (N)	Take off velocity (ms^{-1})	Peak concentric impulse (Ns^{-1})	Peak relative concentric power	Peak concentric power (W)	Reactive strength index (m.s)	20-m split (s)	5-m split (s)	10-20-m split (s)	Peak force (N)	Peak relative force (BW)
Countermovement jump	Peak concentric impulse (Ns^{-1})																
	Take off velocity (ms^{-1})	0.67															
	Peak power (W)	0.98	0.73														
	Peak relative power ($W.kg^{-1}$)	0.51	0.92	0.64													
	Jump height (m)	0.72	1.00	0.77	0.91												
	Peak concentric force (N)	0.81		0.76		0.53											
Drop jump	Take off velocity (ms^{-1})		0.61		0.56	0.59											
	Peak concentric impulse (Ns^{-1})	0.92	0.66	0.91	0.53	0.70	0.80	0.64									
	Peak relative concentric Power ($W.kg^{-1}$)	0.37	0.69	0.40	0.62	0.66	0.33	0.84	0.50								
	Peak concentric power (W)	0.85	0.81	0.85	0.66	0.82	0.68	0.73	0.9	0.79							
	Reactive strength index (m.s)	0.37	0.66	0.39	0.59	0.65	0.32	0.84	0.51	0.99	0.78						
20-m sprint	20-m split (s)		-0.79	-0.51	-0.72	-0.76		-0.63	-0.52	-0.63	-0.64	-0.57					
	5-m split (s)	-0.49	-0.71	-0.53	-0.63	-0.70				-0.58	-0.64	-0.52	0.90				
	10-20-m split (s)		-0.64		-0.67	-0.62		-0.59					0.83	0.58			
Isometric mid-thigh pull	Peak force (N)	0.81		0.77		0.52	0.54		0.75		0.69		-0.62				
	Peak relative force (BW)												-0.57				
Back squat	3 Repetition maximum (kg)	0.87	0.73	0.84	0.55	0.76	0.77	0.57	0.86	0.49	0.82	0.48	-0.72	-0.61	-0.61	0.73	

Correlations: > 0.9 = nearly perfect; 0.7 – 0.9 = very high; 0.5 – 0.7 = high; 0.3 – 0.5 = moderate; < 0.3 small to trivial (not shown)

3.5 Discussion

The purpose of this study was to investigate the inter-day reliability of variables collected from the CMJ, DJ, IMTP and 20-m sprint when performed by adolescent male athletes. The large number of reliable variables found across the range of performance tests indicates that these tests are a reliable measure of strength and power in an adolescent athletic population.

Variables commonly used in CMJ analysis and measured during this study showed similar reliability to those found in adult populations (Cormack et al., 2008b; Moir et al., 2009) (i.e., peak power CV = 3.2%, ICC = 0.98; relative peak power CV = 3.4%, ICC = 0.91; peak force CV = 5.4%, ICC = 0.92 and jump height CV = 3.4%, ICC = 0.96). All these variables showed good reliability as did some less commonly used variables such as peak concentric impulse (CV = 1.6%, ICC = 0.99) and take-off velocity (CV = 1.7%, ICC = 0.97). These variables, although less frequently used warrant consideration in the analysis of CMJ performance given their higher inter-day stability. In addition to the abovementioned variables, some other less commonly used variables also resulted in CV's of less than 10% including concentric and eccentric phase duration (CV = 6.3% and 8% respectively), centre of gravity downwards movement (CV = 7.2%) and ratio of eccentric to concentric duration (CV = 7.6%). These variables should also be considered in the performance analysis of CMJ's as they relate to the changes in technique that may occur from test to test, such as the influence of fatigue where a different jump strategy may be utilised to achieve a similar outcome such as jump height. However, caution should be employed if using these variables as their respective ICC values (Table 3.1) were found to reflect a lower level of reliability at the level of 0.75, even though others (Randell et al., 2011) have considered this an acceptable level of reliability. Of all the variables measured peak RFD showed the poorest reliability (CV = 37.8%, ICC = 0.27) which is similar to research in adults reported by Sheppard et al (2008a). As suggested by the authors a more reliable measure of RFD may involve using an average RFD utilising the average rate of change across all samples in the propulsive portion as opposed to the current method of the largest change of force between two sequential data samples. As stated previously, limited data exists for the CMJ for adolescents. In the literature that is available, Nuzzo et al, (2009) reported a vertical jump peak power r-value of 0.96 for within session test-retest reliability, similar to the value found in the current study (r = 0.98).

As with the CMJ, the DJ variables found in this study on adolescent athletes compared favourably with published data for adults (Feldmann et al., 2011; Hori, Newton, Kawamori, McGuigan, Andrews, Chapman, & Nosaka, 2008). However in general, the inter-day variability found in the DJ was greater than that found in the CMJ. This could be due to the DJ being a less familiar and more complex skill when compared with the CMJ and despite the athletes being 'trained' in the DJ, greater variability existing in the execution of the movement. Unlike the CMJ there is less uniformity in variables reported in the scientific literature for the DJ, with most literature reporting either jump height, reactive strength index or ground contact time depending on the authors preference, reason for testing (i.e. performance versus fatigue monitoring) or assessment tools (Feldmann et al., 2011; Hori et al., 2008; Kurz et al., 2009). However, as shown in Table 3.2, a large number of variables can be extracted from DJ's performed on a force plate with acceptable levels of reliability. Additionally, ICC values (Table 3.2) were also shown to be high further strengthening the use of these variables as reliable measures of DJ performance. Similar to the CMJ, take-off velocity and peak concentric impulse were the two most reliable variables (CV = 4.8%, ICC = 0.85 and 5.1%, ICC = 0.94 respectively). Other variables of note that could be of importance to practitioners utilising this test were, ratio of eccentric to concentric phase duration (CV = 5.8%, ICC = 0.85), both absolute average and peak concentric power (CV = 5.9%, ICC = 0.95 and 6.1%, ICC = 0.95 respectively) and relative concentric power (CV = 6.4%, ICC = 0.92). The reliability of reactive strength index (RSI) reported in adult literature has displayed average reliability (CV =11.3%) (Feldmann et al., 2011) with the authors also stating that RSI had 'negligible utility for explaining 40cm DJ performance'. The current study found a CV of 9.4% (ICC = 0.92), within the accepted 10% range, however due to the number of other variables with stronger reliability the authors also question the continued use of this variable within the analysis of DJ when performance is the desired outcome. A continued use of RSI may be more appropriate where mechanistic or technique changes are of importance, such as the impact of neuromuscular fatigue.

In the one study found examining DJ in adolescents, Quatman et al, (2006) performed an inter-day reliability study as part of a larger research study on a 31-cm DJ. They found peak vertical ground reaction force at take-off to have an ICC of 0.983 and peak vertical jump height an ICC of 0.986. In the current study both these variables were found to be less reliable than a number of other variables measured (Table 3.2), such as take-off velocity and peak concentric impulse. In the current study peak force was not deemed as reliable as its CV (13.9%) was greater than the 10% cut-off mark despite an ICC of 0.77, higher than the 0.75 level mentioned above. This contrast could be due to the difference in population groups. In the Quatman study (2006), all participants listed there primary sport as basketball indicating a high level of uniformity within participants whereas the current study utilised participants from a range of sports which may influence their reactive strength abilities and thus allow greater variability within the group.

Due to the nature of the IMTP test a comparatively smaller number of variables are collected when compared with the jump tests as shown in previous research conducted on adults (McGuigan & Winchester, 2008; Stone et al., 2003; Stone et al., 2005). Peak force and relative peak force both showed an acceptable CV of 6.4% whilst peak force was found to have an ICC of 0.87 and relative peak force an ICC of 0.73. In contrast, peak RFD showed high variability with a CV of 26.1% and an ICC of 0.64. Interestingly, peak force CV was found to be even stronger (CV = 2.9%) in a subsequent study on the same population group by the authors (n = 9) when further familiarisation had been performed (unpublished data). This difference is thought to be due to familiarisation of the test despite a 1 month, pre-testing, familiarisation period during which participants performed the IMTP in a practice session, twice weekly. The follow-up CV (2.9%) matches that found in adult data as reported by McGuigan et al (CV = 2.3% and ICC = 0.96) (2008) and may be due to a greater level of familiarisation with the test in a maximal test effort setting despite the participants having undergone one month of familiarisation previous to the first test session as mentioned above. The strong CV and ICC values for the majority of the variables measures coupled with its ease of execution makes the IMTP an excellent measure for lower body peak force capabilities in athletes whether they be adult or adolescent as long as adequate familiarisation has been performed.

As reported in other reliability studies conducted on adults (Duthie et al., 2006; Fletcher & Jones, 2004), the variables associated with the 20-m sprint showed very high reliability with CVs ranging from as low as 0.8% in the 20-m split to only as high as 2.7% found in the 10-20-m split. The ICC values for all variables were also high, ranging from 0.98 (20-m split) to 0.80 (10-20-m split). As with peak force in the IMTP, a significant difference ($p = 0.05$) was found between tests for the 20-m split. Subjects were considered familiar with the test, the between test differences likely related to acute fatigue experienced by the subjects. Despite difference in mean for 20-m split the 20-m sprint should be considered a reliable measure of performance in an athletic adolescent population group.

The correlation analyses across the four tests showed some (very high to nearly perfect) correlations that could be considered note-worthy. More correlations were found within a specific neuromuscular test, such as CMJ jump height having a nearly perfect correlation with CMJ relative peak power ($r = 0.91$). In assessing correlations between variables across different tests, 20-m split showed a strong negative correlation ($R > -0.7$) with a number of variables from CMJ including take-off velocity, relative peak power and jump height. The lack of correlations found highlights the specific neuromuscular demands of each test and reinforces the need to carefully determine the athletic quality required for performance in any given sport before choosing a test. That is force, low velocity power (CMJ) and high velocity power (DJ/20-m sprint) are all independent qualities that are best assessed via specific assessment tests.

3.6 Practical applications

Neuromuscular testing is an accepted and common practice for assessing and tracking performance in an athletic population. The reliability of these tests and their specific variables must be understood and accounted for when determining whether a performance change is meaningful or the result of typical error associated with the test. In the current study each performance test was found to have reliable variables that could be used to accurately measure performance changes in adolescent athletes. The most reliable performance tests were those that the athletes were most familiar with specifically, the 20-m sprint and CMJ. All CV values of variables associated with the 20-m sprint variables were less than 3% whilst the CMJ had five variables with a CV of less than 5% including peak concentric impulse, take off velocity, peak power, relative peak power and jump height. The DJ and IMTP were the least reliable tests with only drop jump take off velocity having a CV of less than 5% whilst the commonly used RSI had a CV of 9.8%. Both IMTP variables had a CV of 6.4% although as stated previously, subsequent unpublished data from the authors found this to be 2.9% after great familiarisation. This confirms the need to ensure athletes are very familiar with any test that will be used to monitor performance. A consistent unreliable variable was peak RFD as it displayed a CV of between 26-37% dependant on the test used and should not be used in assessing performance in an adolescent population with the current calculation method. Given that each test measures slightly difference physical qualities, the decision ultimately lies with the strength and conditioning coach to decide which performance measure(s) is the best indicator of performance for their respective athletes. This decision should include which variable is the most relevant to their, sport its reliability and has the athlete received adequate familiarisation.

Chapter 4

Body composition, morphological and neuromuscular adaptations. Preparatory vs competition period strength training in adolescent athletes.

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The aim of this study was to use a variety of body composition, morphological and neuromuscular tests to determine the adaptations of adolescent athletes to strength programs performed during a preparatory (six-week) and competition period (nine-week) of an annual training cycle. The reliability of the neuromuscular tests utilised were determined previously and are presented in Chapter 3. This study was designed to be reflective of the various training blocks performed in an annual training cycle.

4.1 Abstract

To examine the effects of periodised strength training blocks on body composition, muscle morphology and neuromuscular performance in adolescent athletes. Fourteen subjects (age 16.5 ± 1.1 y, height 171.3 ± 6.3 cm, body mass 65.0 ± 11.2 kg) performed the following tests before and after two strength training blocks (competition and preparatory); whole body DEXA, ultrasound of the vastus lateralis (VL), countermovement jump (CMJ), drop jump (DJ), isometric mid-thigh pull (IMTP), 20-m sprint and 3RM back squat. Results were assessed for magnitude of change (effect sizes [ES]) for differences across training blocks. Body composition showed trivial changes after both periods. VL thickness increased (7.5 ± 3.3%) as did CMJ variables (e.g., jump height = 4.9 ± 3.1%) after the preparatory period. Most DJ variables decreased during both training periods, whilst IMTP measures only improved during the competition period (peak force = 11.0 ± 6.2%). Most 20-m sprint variables showed positive effects (e.g., 5m split = 5.0 ± 4.7%) following the competition period. Whilst other training factors may contribute to changes in NM performance it is likely that a specific preparatory period strength program will result in greater improvements in dynamic lower body strength/power measures compared to one conducted in-

season in adolescent male athletes. Competition period strength training in conjunction with specific athletic training may contribute to a beneficial impact on speed.

4.2 Introduction

Athletic preparation, specifically the development of relevant strength and power indices related to improving sport performance are a major focus of S&C coaches. Historically, monitoring improvements in strength and power were performed by RM tests conducted on the exercises employed within a resistance training program (Baker & Newton, 2008; Lyttle et al., 1996). More recently, neuromuscular tests such as the CMJ (McGuigan et al., 2008; Riggs & Sheppard, 2009), DJ (Flanagan et al., 2008; Quatman et al., 2006), IMTP (Haff et al., 2005; Winchester et al., 2008) and sprints (Gathercole et al., 2015a; Seitz et al., 2014) have been commonly used to monitor physical performance. These tests provide specific performance feedback that may otherwise be undetectable by standard RM testing, and allowing the S&C Coach to monitor the impact of any resistance training stimulus with greater specificity.

In addition to neuromuscular adaptations, resistance training can also positively impact the body composition and morphological profile of an athlete (Campos et al., 2002; Cormie et al., 2010; Uchida et al., 2006), with improvements in lean muscle mass parameters (Alegre et al., 2006; Campos et al., 2002; Cormie et al., 2010) and decreases in fat mass being linked to increases in performance (Ahtiainen et al., 2003). Specific changes in muscle thickness (Ahtiainen et al., 2003; Cormie et al., 2010; Holm et al., 2008) and muscle pennation angle (Alegre et al., 2006; Cormie et al., 2010; Kawakami et al., 1995) have also been linked to specific improvements in force production capabilities.

S&C coaches use a variety of resistance training protocols to elicit the physiological responses desired for maximizing athletic performance. Maximum strength, or force production is a specific training modality that is regularly employed in the development of athletes with such training regimens typically involving low repetitions (1-5) of very high loads (85-100% 1RM)(Kraemer & Ratamess, 2004). In contrast to this, power training typically involves low repetitions but performed at significantly lower loads (20-60% 1RM)(Winchester et al., 2008), although this may be dependent on the specific exercise used and whether ballistic or non-ballistic exercises are performed (Kraemer & Ratamess, 2004). Whilst the effects of either in-season (Baker, 2001; Veliz, Requena, Suarez-Arrones, Newton, & de Villarreal, 2014) or pre-season (Hansen, Cronin, Pickering, & Newton, 2011) strength and/or power training have been documented previously, the authors are unaware of any research comparing in-season to pre-season strength training periods.

The effects of maximum strength training on athletic performance assessed via improvements in CMJ (Cormie et al., 2009; Gathercole et al., 2015b), DJ (Argus et al., 2012), IMTP (Stone et al., 2003) and sprint performance (Dasteridis et al., 2011; Seitz et al., 2014) have been linked to improved athletic performance and as such are now considered common tests for tracking performance in senior athletes. However, research studying the effect of resistance training programs on body composition, morphological and neuromuscular measures in various training phases in adolescent athletes has not yet been documented. Therefore, the aim of this study was to compare the effects of competition and preparation period maximum strength resistance training programs on body composition, morphological and neuromuscular parameters in adolescent male athletes.

4.3 Methods

Approach to the Problem

To determine the effects of the maximum strength training programs on body composition, morphological and neuromuscular parameters the subjects performed a test battery consisting of a full-body DEXA scan, ultrasound of the vastus lateralis (VL) and performance measures (three CMJ's, three DJ's, three 20-m sprints and two IMTP's). This test battery was performed three times during the 18-week study period (Figure 4.1). This period was chosen to coincide with competition and preparatory training periods in the athletes' annual plan where training could be controlled and the baseline, post-competition period and post-preparation period testing sessions could be completed without interruption.

January				February				March					April				May	
Competition Period								Preparation Period										
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18

Testing was conducted in weeks 1 (baseline), 11 (post-competition), 18 (post-preparation)

Figure 4.1. The 18-week training study period as a part of the standard yearly training plan for the athletes

Participants

Fourteen adolescent male athletes were recruited to participate in the study. Subjects (age 16.5 ± 1.1 y, height 171.3 ± 6.3 cm, body mass 65.0 ± 11.2 kg and 3RM back squat 82.6 ± 23.7 kg) were all students at an elite sports academy and competed in either squash, taekwondo or fencing. Each athlete undertook a minimum of eight training sessions per week including sport specific and physical development training plus occasional competitions. Due to the training structure used within the academy, this group of athletes experienced a large deal of uniformity in their weekly training schedule, performing all physical preparation sessions under the supervision of the same S&C coach. Whilst the sport specific training sessions for each athlete was inherently different from a skill development perspective, the focus of these sessions during this period was for sport skill development only. As such it was assumed that the physical demands of these sessions were low, and of a similar level across athletes and hence should not be considered a co-variate for the purpose of this study. Each athlete had a minimum of two years of resistance training experience and was familiar with all of the tests used in the study. All subjects received a clear explanation of the study, including risks and benefits of participation and provided written consent before the start of the study. The study was approved by the James Cook University Human Ethics Committee.

Procedures

Body composition

Prior to each neuromuscular test session, the athletes performed a whole-body DEXA scan to assess body composition (GE Healthcare, Lunar iDXA, Madison, USA). These scans were performed at similar times in the morning before breakfast and prior to any exercise being performed. The same qualified technician was used for all DEXA scans to help maximise reliability. All scans were performed following the same protocol with subjects arriving 15 minutes prior to the scan and changing into appropriate clothing before sitting quietly for 10 minutes. Body composition changes assessed including total body mass, total lean body mass, legs lean mass, arms lean mass, total bone mineral content (BMC), total tissue mass and total fat mass. The typical error of measurement for the technician was 1.41% (determined from the variable percent body fat).

Morphological assessments

The athletes also had an ultrasound scan of the VL (Siemens, Acuson 500, Erlangen, Germany) to assess *in vivo* muscle architecture prior to each neuromuscular test session. The same experienced technician conducted all the ultrasound scans to help maximise reliability. For the initial scan the technician measured the distance between the centres of the greater trochanter and the lateral condyle of the head of the femur of the subjects' dominant leg and marked a distance equal to 50% of the calculated thigh length. This distance was recorded and used for all subsequent trials. Digital ultrasound images were taken of the scan sight and for all subsequent scans so as to best match the analysis site in all trials. These images were analysed post session to determine muscle thickness and pennation angle as previously described by Cormie et al (2010). The chosen leg was scanned three times; first with the leg supine, in full extension with muscles completely relaxed, secondly in double flexion with both the knee/hip flexed to 90 degrees and third, again in full extension as per the first scan. The results from the 2 repeat full extension scans were averaged and used in subsequent analyses.

Neuromuscular assessments

Before commencing the neuromuscular assessments, the subjects performed a 10 minute, standardized dynamic warm-up which included dynamic running drills, dynamic stretches, two sets of three CMJ's (60% and 90% intensity), two 25-m submaximal sprints (70% and 90% intensity) and one set of three DJ's (60%, 80% and 100% intensity). A minimum of three minutes rest was given after the warmup before testing began to minimize carry-over of fatigue. The neuromuscular tests were completed in the following order; three maximal CMJ's, three maximal DJ's from a 40 cm box, three maximal 20-m sprints and two maximal IMTP's. One minute rest was allowed between each CMJ and DJ, two minutes rest was allowed between each 20-m sprint and three minutes rest was given between IMTP trials. A minimum of two minutes rest was given between the different neuromuscular tests. The test protocols for these neuromuscular tests have been detailed previously (Haines, Bourdon, & Deakin, 2016).

In the week preceding the test sessions 3RM back squat was determined for each athlete. This required the athlete to squat until their thighs were parallel with the floor. Squat depth was monitored visually by the same experienced tester who observed all trials to ensure uniformity between subjects. 3RM was determined after specific warm-up sets were performed at 50% (five to eight repetitions), 70% (five repetitions) and 90% (one to three repetitions) of their previous 3RM. A five minute rest period was allowed between efforts of 90% and above (Winchester, Erickson, Blaak, & McBride, 2005).

Reliability of test protocols

The reliability of CMJ variables, as indicated by a percent typical error via coefficient of variation (CV) were: peak concentric impulse (1.6%), peak power (3.2%), relative peak power (3.4%) and jump height (3.4%). Similarly, DJ variables were also found to be reliable: take-off velocity (4.8%), peak concentric impulse (5.1%), peak concentric power (6.1%) and relative peak concentric power (6.4%). The 20-m sprint showed very strong reliability with variables ranging from a minimum of 0.8% (20-m split) to a maximum 2.7% (10 to 20-m split). Within the IMTP, the two key variables of interest were seen to reliable for this population group with both peak force and relative peak force having a CV of 6.4%. The reliability data presented above and additional reliability for all variables analysed in this study were taken from previous research by the authors (Haines et al., 2016). Previous analysis in this laboratory had determined the 3RM back squat reliability to have a CV of 6.1%.

Training protocols

Each week of the competition period (weeks 2 to 10) included zero to two maximum strength sessions (Table 4.1 – Lifting session; 9 total sessions over the 9-week period) and five to six sport specific training sessions that included one speed and agility and one conditioning session. The same strength training program was performed in two four-week blocks, block 1 (weeks 2 to 5), and block 2 (weeks 7 to 10). Week 6 was a deload week during which no strength sessions were performed due to school scheduling restrictions whilst the program was performed twice in week 10. Each week of the preparation training block (weeks 12 to 17) included two to three maximum strength sessions (Table 4.2 – Lifting session; 15 total sessions over the 6-week period) and five to six sport specific training sessions that incorporated one to three speed and agility and conditioning sessions.

Table 4.1. Strength training program for the competition period

Competition Period Exercises				
Exercise	Week 2 (7)	Week 3 (8)	Week 4 (9)	Week 5 (10)
Drop Jumps	4 x 5 @ 30cm	5 x 3 @ 40cm	4 x 5 @ 40cm	3 x 3 @ 40cm
Countermovement Jumps (bodyweight)	2 x 5	3 x 3	2 x 5	3 x 3
Back Squat	4 x 6 @ 77%	2 x 6 @ 77%, 2 x 4 @ 81%	4 x 4 @ 81%	3 x 3 @ 86%
Bench Pull	4 x 8 @ 73%	4 x 6 @ 77%	4 x 4 @ 81%	3 x 3 @ 86%
Dumbbell Press	4 x 8 @ 73%	4 x 6 @ 77%	4 x 4 @ 81%	3 x 3 @ 86%
Isometric Mid-Thigh Pull (maximal)	2 x 6 s	3 x 3 s	3 x 5 s	2 x 5 s

Weeks (in brackets), indicate the corresponding set and rep scheme used in the second block of the competition period strength program.

Table 4.2. Strength training program for the preparation period

(A) Preparation Period Exercises							
Day 1	Day 2	Week 12	Week 13	Week 14	Week 15	Week 16	Week 17
Sessions per week		2	3	2	3	2	3
Intensities (% 1RM)		85%	88%	91%	88%	85%	91%
Back Squat	Deadlift	4 x 5	4 x 4	2 x 4, 3 x 3	4 x 4	4 x 5	5 x 3
Romanian Deadlift	Split Squat	4 x 5	4 x 4	2 x 4, 3 x 3	4 x 4	4 x 5	4 x 3
Single Leg Press	Leg Press	4 x 5	4 x 4	2 x 4, 3 x 3	4 x 4	4 x 5	3 x 3
Bench Press	Decline Press	4 x 5	4 x 4	2 x 4, 3 x 3	4 x 4	4 x 5	4 x 3
Bench Pull	Chin-Ups	4 x 5	4 x 4	2 x 4, 3 x 3	4 x 4	4 x 5	4 x 3
Total lower body reps for each week		120	144	102	144	120	108

* The same intensities (% 1RM were performed on day 1 and day 2 of the program.

Statistical Analyses

To asses if the effect of training phase on each variable was practically beneficial, trivial or harmful, the data were assessed using a magnitude-based inferences approach (Hopkins et al., 2009). These methods were selected because traditional statistical approaches often do not indicate the magnitude of an effect, which is typically more relevant to athletic performance than any statistically significant effect.

Of interest was the magnitude of changes in body composition, morphological and neuromuscular variables between baseline (week 1) to post-competition (week 11) and post-competition (week 11) to post-preparation (week 18) testing sessions. All analyses were performed using a modified statistical spreadsheet (Hopkins, 2006b). ES were calculated using 0.2 x between-athletes SD with the following threshold inferences used: ≤ 0.2 (trivial), >0.2 (small), >0.6 (moderate), >1.2 (large), >2.0 (very large) and >4.0 (extremely large) (17).

In addition, a qualitative description of the differences were assessed with the change/difference evaluated as follows: <0.5%, almost certainly not; 0.5-5%, very unlikely; 5-25%, unlikely; 25-75% possibly; 75-95%, likely; 95-99.5%, very likely and >99.5%, almost certainly. If the 90% confidence intervals of the ES overlapped both ES small boundaries, then changes were deemed unclear (17).

4.4 Results

A total of nine subjects completed the DEXA, ultrasound, CMJ, DJ and IMTP tests at all three test sessions, five subjects choosing to voluntarily withdraw from the study. Only eight subjects completed the 20-m sprint test due to a restriction from medical staff for one subject, this however had no impact on any of the other tests. Training compliance during the competition and preparation periods was 88% and 92% respectively. Mean ± standard deviation (SD) for all test variables are reported in Table 4.3.

Table 4.3. Athlete test results. Mean ± SD

	Baseline	Post Competition	Post Preparation
Countermovement Jump			
Take off velocity ($m.s^{-1}$)	2.77 ± 0.25	2.73 ± 0.23	2.80 ± 0.25
Peak power (W)	3704 ± 983	3612 ± 869	3794 ± 932
Relative peak power ($W.kg^{-1}$)	54.9 ± 6.9	53.1 ± 5.4	54.8 ± 5.6
Jump height (m)	0.42 ± 0.07	0.41 ± 0.07	0.43 ± 0.07
Peak concentric force (N)	1606 ± 306	1686 ± 363	1780 ± 370
Relative Peak concentric force (kg.bm)	2.56 ± 0.35	2.53 ± 0.19	2.64 ± 0.24
Peak concentric impulse (N.s)	195.7 ± 50.1	195.7 ± 47.2	203.2 ± 48.0
Concentric Phase duration (s)	0.28 ± 0.049	0.28 ± 0.036	0.28 ± 0.028
Drop Jump			
Take off velocity ($m.s^{-1}$)	2.40 ± 0.27	2.24 ± 0.21	2.21 ± 0.3
Peak power (W)	4218 ± 1130	4134 ± 1227	3906 ± 1026
Relative peak power ($W.kg^{-1}$)	62.9 ± 11.5	60.7 ± 10.6	56.9 ± 10.7
Jump height (m)	0.30 ± 0.06	0.26 ± 0.05	0.25 ± 0.06
Average eccentric power (W)	3462 ± 654	3749 ± 853	3623 ± 928
Relative average eccentric power ($W.kg^{-1}$)	52.0 ± 6.5	55.3 ± 7.5	52.4 ± 7.4
Peak concentric impulse (N.s)	165.1 ± 36.8	155.3 ± 36.1	152.6 ± 31.6
Average concentric power (W)	2402 ± 607	2318 ± 660	2196 ± 577
Relative average concentric power ($W.kg^{-1}$)	35.8 ± 5.6	34.0 ± 5.6	32.1 ± 6.4
Reactive strength index ($m.s^{-1}$)	1.24 ± 0.29	1.19 ± 0.30	1.08 ± 0.30

	Baseline	Post Competition	Post Preparation
Isometric Mid-Thigh Pull and 3RM Back Squat			
Peak force (N)	2238 ± 527	2466 ± 469	2555 ± 551
Relative peak force (BW)	3.39 ± 0.40	3.71 ± 0.30	3.8 ± 0.54
3RM Back Squat (kg)	86.1 ± 28.8	91.7 ± 27.7	105.7 ± 27.7
20 m Sprint			
5-m split (s)	1.12 ± 1.10	1.07 ± 0.06	1.1 ± 0.07
10-m split (s)	1.88 ± 0.15	1.80 ± 0.10	1.83 ± 0.10
20-m split (s)	3.20 ± 0.21	3.12 ± 0.17	3.12 ± 0.14
5-10-m split (s)	0.74 ± 0.05	0.72 ± 0.04	0.72 ± 0.03
10 – 20-m split (s)	1.31 ± 0.07	1.30 ± 0.09	1.29 ± 0.06
DEXA and Ultrasound			
Total mass (kg)	66.74 ± 11.80	67.50 ± 11.84	68.15 ± 11.01
Total lean mass (kg)	53.71 ± 9.54	54.03 ± 9.30	54.69 ± 8.88
Legs lean mass (kg)	18.77 ± 3.86	18.89 ± 3.68	19.37 ± 3.51
Arms lean mass (kg)	6.60 ± 1.39	6.64 ± 1.32	6.77 ± 1.29
Total bone mineral content (kg)	2.86 ± 0.40	2.91 ± 0.38	2.93 ± 0.37
Total tissue mass (kg)	63.87 ± 11.44	64.59 ± 11.51	65.22 ± 10.68
Total fat (kg)	10.16 ± 3.38	10.56 ± 3.99	10.54 ± 3.4
Average angle supine (°)	19.90 ± 5.68	17.90 ± 2.89	17.60 ± 5.08
Angle double flexion (°)	12.10 ± 4.31	11.30 ± 3.27	12.20 ± 3.12
Average thickness supine (mm)	25.06 ± 3.88	24.56 ± 2.92	26.40 ± 3.69

Body composition

No clear differences were found in any of the body composition measures conducted over the 18-week study period (Figures 4.2a & 4.2b).

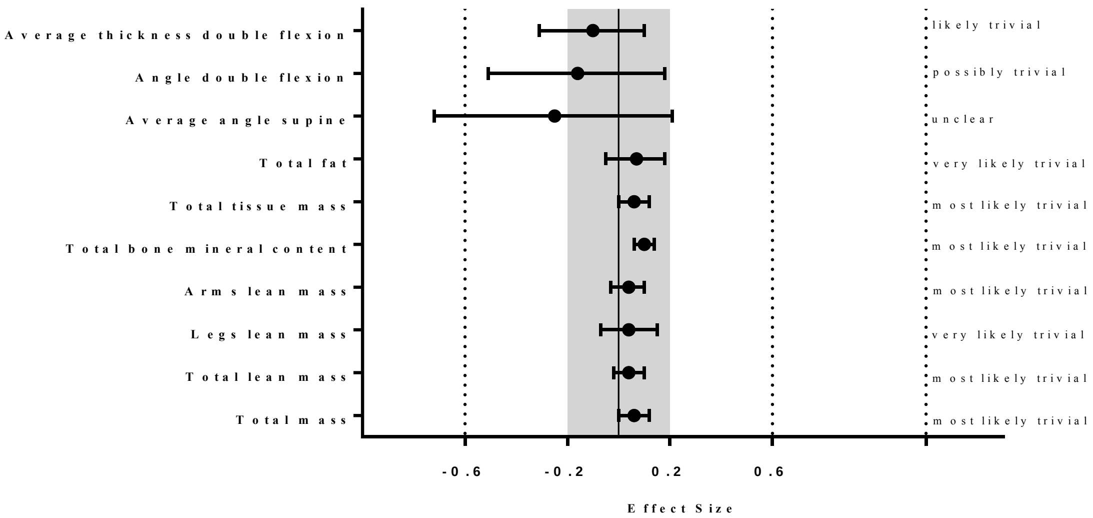

Figure 4.2a. Baseline vs Post-Competition effect sizes (mean ± 90% confidence limits) and qualitative magnitude based inference for DEXA and ultrasound scans

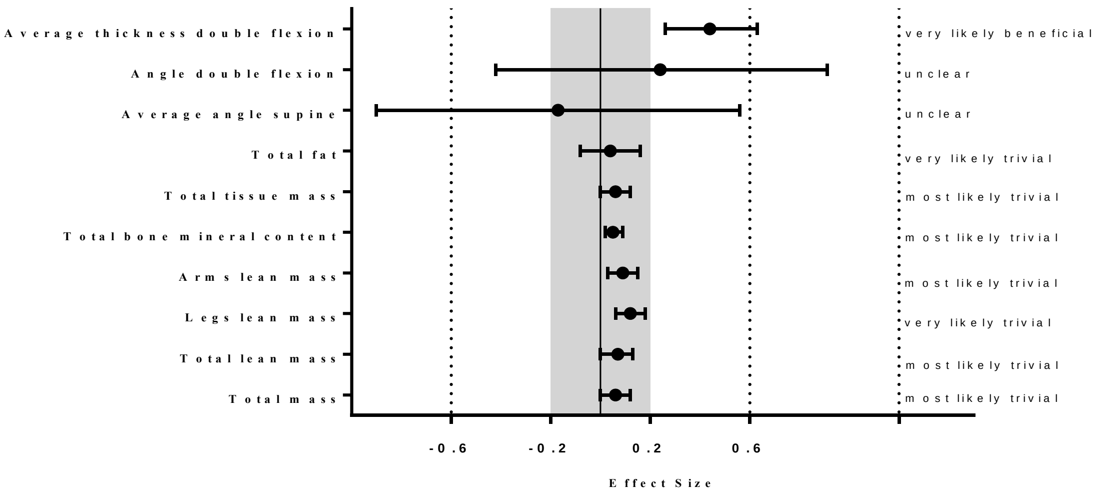

Figure 4.2b. Post-Competition vs Post-Preparation effect sizes (mean ± 90% confidence limits) and qualitative magnitude based inference for DEXA and ultrasound scans

Morphological measures

No observable differences were seen in the VL ultrasound scans during the competition block, whilst a very likely beneficial difference in the mean (mean ± 90% CL) for muscle thickness (7.3% ± 2.9%, chances that the true difference were higher/trivial/lower, 98/2/0 %) measured in the supine position following the preparation training block. No clear change was seen in pennation angle over the course of the preparation period (Figures 4.2a & 4.2b).

Neuromuscular performance

3RM back squat showed likely trivial changes (7.5% ± 4.5%, 44/56/0 %) during the competition period (Figure 4.3a) however it showed a very likely beneficial improvement (16.9% ± 5.2%, 99/1/0 %) during the six-week preparation training block (Figure 4.3b).

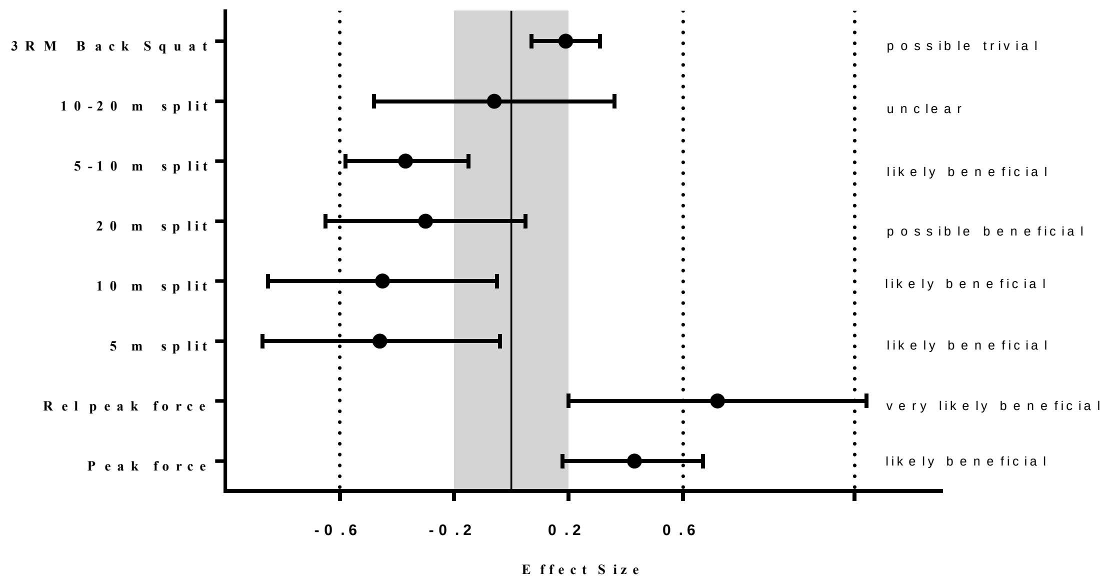

Figure 4.3a. Baseline vs Post-Competition effect sizes (mean ± 90% confidence limits) and qualitative magnitude based inference for 3RM back squat, 20-m sprint and isometric mid-thigh pull

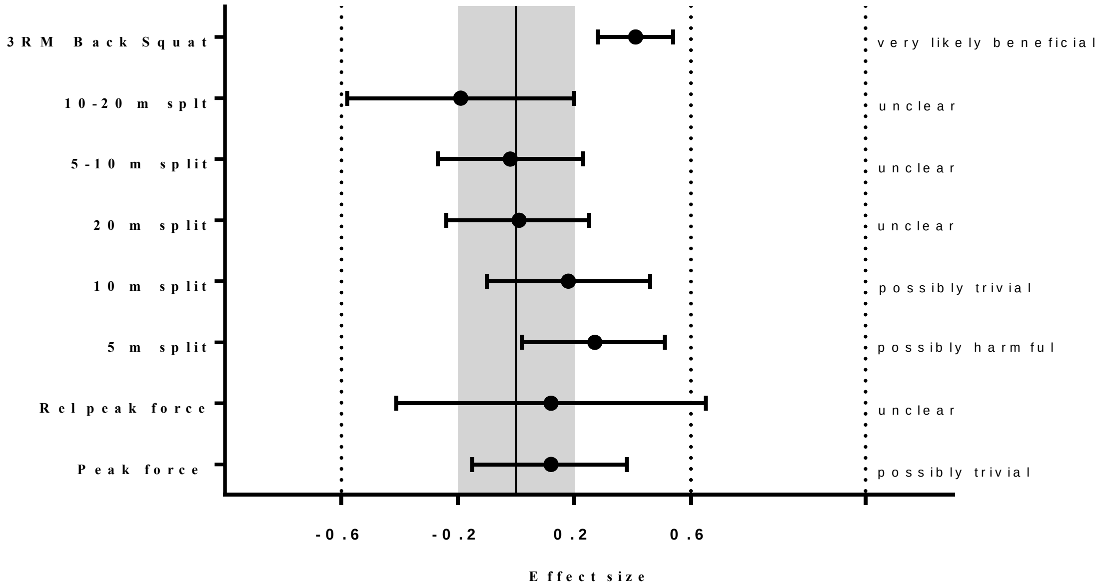

Figure 4.3b. Post-Competition vs Post-Preparation effect sizes (mean ± 90% confidence limits) and qualitative magnitude based inference for 3RM back squat, 20-m sprint and isometric mid-thigh pull

The competition block produced a possibly beneficial change in one of the CMJ variables measured, peak concentric force (4.4% ± 6.5%, 52/46/2 %). However, a possibly negative change was seen for relative peak power (-3.1% ± 4.5% 2/41/57 %) during this period. In contrast, the six-week preparation training block resulted in improvements in several CMJ variables with possible increases in relative peak power (3.3% ± 3.5%, 60/39/1 %), jump height (4.9% ± 3.1%, 73/27/0 %), and peak concentric force (5.7% ± 7.4%, 64/34/2 %) (Figures 4.4a & 4.4b).

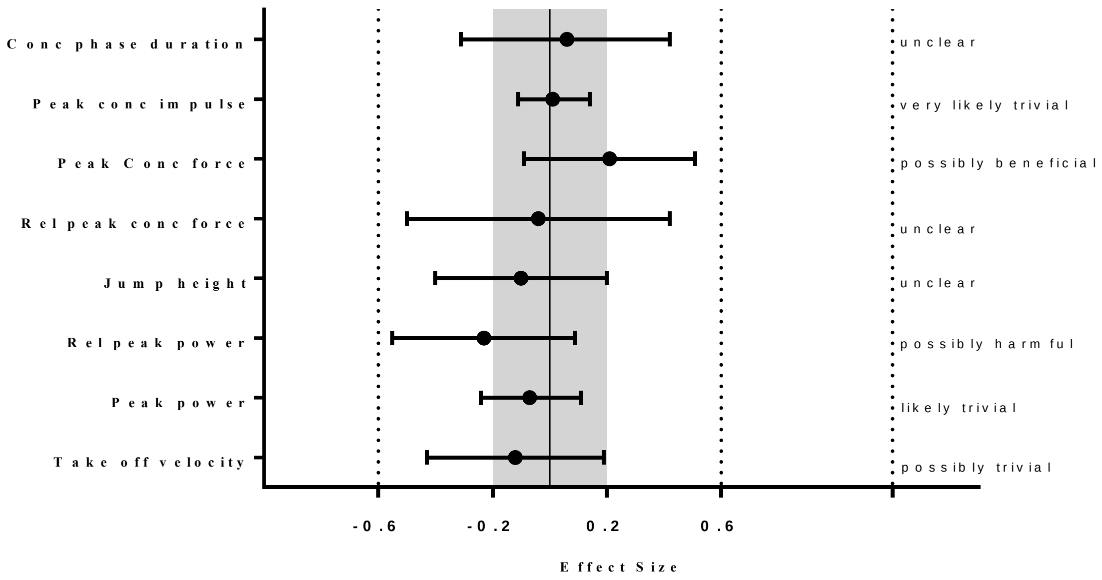

Figure 4.4a. Baseline vs Post-Competition effect sizes (mean ± 90% confidence limits) and qualitative magnitude based inference for countermovement jump

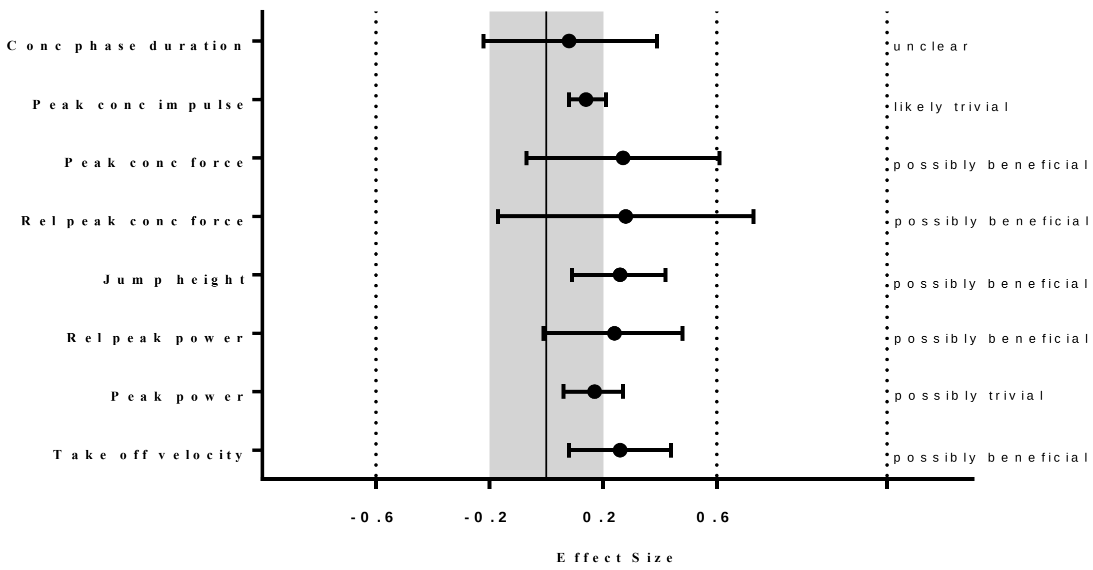

Figure 4.4b. Post-Competition vs Post-Preparation effect sizes (mean ± 90% confidence limits) and qualitative magnitude based inference for countermovement jump

Drop Jump performance showed a decrease after the competition block in a number of variables with a likely decrease in jump height (-12.7% ± 17.0%, 3/15/85 %) and a possible decrease in peak concentric impulse (-5.9% ± 7.1%, 1/38/62 %). This decrease continued during the preparation block with a likely decrease seen in relative concentric peak power (-6.6% ± 7.0%, 3/22/75 %), RSI (-10.1% ± 11.2%, 1/19/80 %) and relative average eccentric power (-5.2% ± 5.7%, 1/19/80 %) (Figure 4.5a & 4.5b).

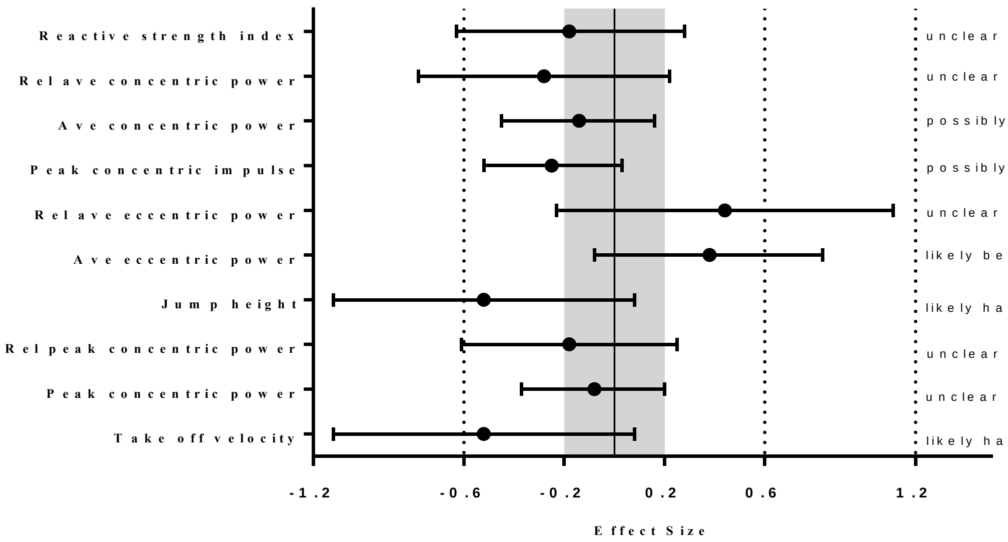

Figure 4.5a. Baseline vs Post-Competition effect sizes (mean ± 90% confidence limits) and qualitative magnitude based inference for drop jump

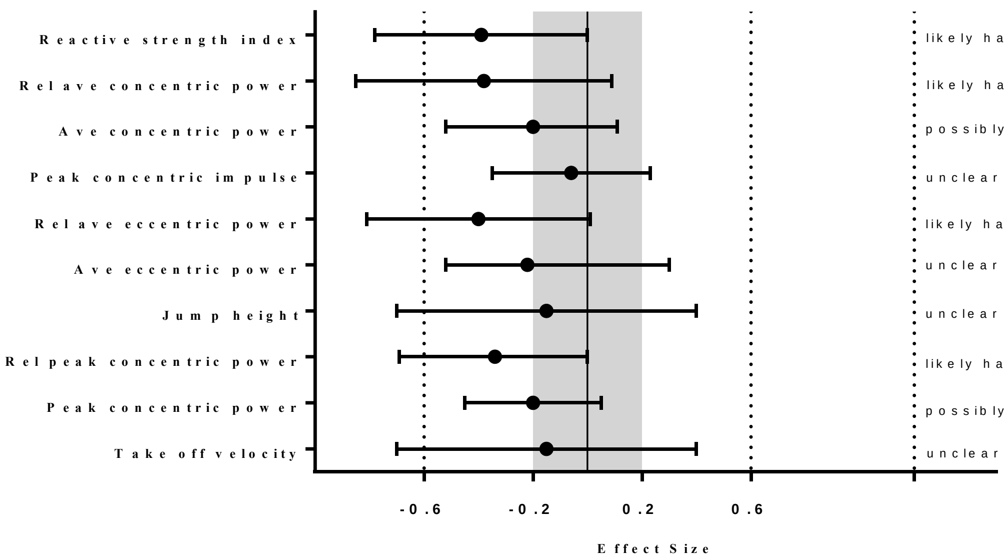

Figure 4.5b. Post-Competition vs Post-Preparation effect sizes (mean ± 90% confidence limits) and qualitative magnitude based inference for drop jump

Peak force and relative peak force measures during the IMTP showed a likely and very likely beneficial improvement after the competition block (11.0% ± 6.2%, 94/6/0 % & 9.8% ± 7.0%, 95/4/1 %) whilst all other variables showed trivial or unclear changes at every time point (Figure 4.3a & 4.3b).

Subjects improved in all variables measured in the 20-m sprint after the competition block except 10-20-m split (unclear). There was a likely decrease in 5-m split (-5.0% ± 4.7%, 1/13/86 %), 10-m split (-4.0% ± 3.7%, 1/13/86 %) and 5-10-m split (-2.5% ± 1.5%, 0/10/90 %) whilst the preparation block resulted in a possible increase in 5-m split (3.0% ± 2.8%, 68/31/1) (Figure 4.3a & 4.3b).

4.5 Discussion

This study compared changes in body composition, morphological and neuromuscular adaptations to maximum strength programs conducted performed in conjunction with other sport training during competition and preparation periods in adolescent male athletes. As such this study provides novel information on the adaptations that occur within an adolescent athletic population in response to maximum strength training performed as part of the athlete's overall sport preparation at various times during an annual training cycle. The key findings of this study were; 1) VL thickness increased during the 6-week preparation period training block and this was reflected in a concomitant increase in 3RM back squat during the same period, 2) CMJ variables showed the most change of the various neuromuscular tests in response to the preparation period training block, and 3) multiple 20-m sprint variables had positive changes during the competition training block.

Body composition

No changes were seen in any of the body composition variables measured during either of the training periods. The lack of changes related to body composition such as body fat, lean mass and bone mineral content measures was expected due to the nature of the training (i.e. maximum strength training) which is traditionally associated more with neuromuscular changes rather than body composition changes (Folland & Williams, 2007).

Morphological

Changes to muscle architecture were not observed during the competition training periods. As reported in Figure 4.2a, the competition training period stimulus was insufficient to have any meaningful impact on VL thickness. This period of reduced strength training volume also resulted in unclear changes in VL pennation angle when measured in the supine position (ES = -0.25 ± 0.47).

It was unclear if the preparation period training had any meaningful effect on pennation angle, however a small (ES = 0.44 ± 0.18) increase was observed in VL thickness during this block. Although not a direct measure of muscle architecture, these results suggest that non-invasive ultrasound method may be beneficial for assessing morphological changes that may take place during maximum strength training and hence its contribution towards increases in muscle force production and overall improvements in athletic performance (Cormie et al., 2010).

Neuromuscular

Back squat strength showed a very likely beneficial effect (99% chance) of improving over the preparation period and a possibly trivial effect (56% chance) of change during the competition period. These results indicate that an average of one session a week (i.e. competition period) may be effective in maintaining performance in the 3RM back squat, whilst increasing the number of sessions to two to three sessions per week as done in the preparation period likely improves the chance of having a positive impact on performance (16.5% effect vs 7.5% effect). This is not surprising given the greater volume of strength training conducted during the preparation period. It also reinforces previous research that indicates the benefits of designated ‘strength blocks’ during the annual cycle, even when working with adolescent athletes (Christou et al., 2006; Santos & Janeira, 2008). These results also reinforce the concept of specificity of training, i.e., the majority of the training during the preparation period was focused on high force/low velocity lower body training which is similar to the contraction type that occurs during a 3RM back squat test.

Although the improvements in 3RM back squat where not reflected in body composition changes such as increases in leg lean mass (Figure 4.2b), some of the improvement could be linked to the increase in VL thickness. This increase in muscle thickness (7.3%) after the heavy force training is similar to findings from other researchers (Cormie et al., 2010) and suggests that a change in muscle thickness has a positive impact on force generation ability.

The IMTP, another high force/low velocity neuromuscular measure did not have as conclusive results as the 3RM back squat. The preparatory period showed no clear effects on peak force and relative peak force (Figure 4.3b) whilst the competition period training resulted in a likely and very likely chance that there was an increase in peak force and relative peak force respectively. The differences between 3RM back squat and IMTP results could be explained by specificity of training (i.e., a greater range of movement, dynamic exercise (3RM back squat) vs. an isometric exercise (IMTP) as seen in other research (Stone et al., 2003). However, although a four-week familiarization program was conducted during resistance training sessions prior to the initial testing block in week 1, it is possible that the differences may also be due to lack of familiarity of the IMTP as a testing procedure rather than a training exercise. The results of a concurrent reliability study showed significant improvements in peak force across trials indicating that 'training familiarization' may not equate to 'testing familiarization' and that the additional motivation and intent present during a testing session may not be accounted for during a familiarization period (Haines et al., 2016). These data should not be interpreted to assume that dynamic lower body strength training has no impact on isometric peak force measures, as this has been shown otherwise in previous research (Beattie et al., 2016).

The 20-m sprint showed mixed results across variables and training periods. During the preparation period no positive meaningful changes in 20-m sprint variables were seen. There was however a possible chance that 5-m split time was slower (ES = 0.27 ± 0.25). During the competition period almost all 20-m sprint variables showed small improvements with likely improvements in 5-m, 10-m, 5-10-m split and possible improvements in 20-m split. Other researchers have shown a link between increase in force development via high force/low velocity training and faster sprint times (Cormie et al., 2010; Seitz et al., 2014). However the data in the current study supports a theory suggesting acute physiological and performance characteristics will move towards the predominant training modality performed during a given cycle (Brandon et al., 2015). That is, within the current study more time was given to higher velocity training during the competition period as the focus was more on sport specific training and competition than during the preparation period where the combined training stimulus had a higher volume of force related training. This is substantiated by research that ballistic power training resulted in greater improvements in sprint speed variables then heavy strength training (Cormie et al., 2010).

Both training periods saw meaningful changes occur across multiple variables for the CMJ. During the preparation period a possibly small beneficial effect on take-off velocity (2.6%), relative peak power (4.8%) and jump height (4.9%) (Figure 4.4b) was reported. These results were in direct contrast with the competition period after which the majority of variables showed trivial effects from the program and relative peak power even showing a possible small decrease (-3.1%). The positive improvement seen in CMJ performance after the preparation period confirms the benefit of performing lower body strength exercises such as the back squat and deadlift. The underlying gains made in dynamic strength as measured in the 3RM back squat also showed some transfer to the CMJ.

Results from the DJ were the most confounding with performance across the majority of variables showing a steady decline in performance across the entire study (Figures 4.5a and 4.5b). During the preparation period the majority of variables measured showed chances of a negative effect with some (relative peak power, relative average concentric power and RSI) showing a likely negative effect. This was less pronounced during the competition period with take-off velocity and jump height both having a likely small negative effect whilst peak concentric impulse showed a possibly harmful effect on performance. These results indicate that performance in the DJ, which is reliant on the ability to develop high levels of force in a very short time (contact times of approximately 200 ms or less), was possibly 'detrained' during the preparation period and to a lesser extent during the in-season program. Similar to the CMJ results this is not surprising given the nature of training performed during both periods. No specific reactive strength or short (< 200 ms) contraction time exercise was performed during either of these training periods and, as shown previously (Viitasalo et al., 1998), specific neuromuscular training that utilizes a strong eccentric stretch may be needed to elicit better performance in the DJ.

4.6 Conclusion

The current study suggests that in adolescent male athletes a specific preparation period will result in improvements in dynamic lower body strength. Whilst during a competitive period incorporating only one strength session per week dynamic lower body strength can be maintained. Improvements in dynamic lower body strength, partly driven by changes to the associated muscles such as increased muscle thickness can also transfer to similar movement pattern dynamic performance measures (e.g. CMJ). However, during such a period it is unlikely that changes in sprint speed will occur unless similar sprint type training is integrated into the program.

For S&C coaches to see concurrent increases in sprint speed they should also include faster contraction velocity exercises such as jumping or sprint related training as was seen during the competition period. This has implications across a wide range of sports as many benefit from improvements in sprint speed as well as CMJ.

These findings should influence the organisation of training throughout a year and remind S&C coaches to appropriately place their various training blocks in the annual cycle allowing them to maximise targeted qualities (i.e. utilising preparation periods to develop maximal strength and periods closer to or during competition to improve sport specific performance qualities).

Chapter 5

Acute effects and recovery from a maximum strength session at different points of the annual cycle in adolescent athletes

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This chapter continues on from the research presented in Chapter 4 and was designed to investigate the response of adolescent athletes to a fatiguing maximum strength training session and the subsequent recovery profile. The same neuromuscular tests used in Chapters 3 and 4 were employed and neuromuscular readiness was monitored 0-, 4-, 24- and 48-h post training session.

5.1 Abstract

Purpose: To examine the acute effects of a fatiguing maximum strength session at three different periods in the annual training cycle on neuromuscular performance in adolescent athletes. **Methods:** Young male athletes (age 16.5 ± 1.1 y, height 171.3 ± 6.3 cm, body mass 65.0 ± 11.2 kg and 3RM Back Squat 82.6 ± 23.7 kg) performed a battery of tests before, 0-, 4-, 24- and 48-h after a fatiguing maximum strength session. Tests included a CMJ, DJ, IMTP and 20-m sprint. Meaningful changes in performance were assessed using a magnitude-based inferences approach with qualitative descriptors of change also calculated. **Results:** DJ performance showed the most sensitivity to fatigue immediately post and up to 48 h later. Stronger athletes tended to show an improved ability to recover from fatigue, especially in the DJ and 20-m sprint. **Conclusion:** Maximum strength training elicits different fatigue time course patterns in the CMJ, DJ, IMTP and 20-m sprint highlighting the importance of appropriate placement within the athlete's weekly schedule. Additionally, tolerance to such training sessions may be affected by the time within the annual cycle and consequently, the athlete's exposure to maximum strength stimuli.

5.2 Introduction

Maximum strength training is an established and common place mechanism used by athletes to improve athletic performance (Baker, 2001; Harries et al., 2016; Suchomel et al., 2016). This type of training typically involves low repetitions (1-5) and high intensities (>80% 1RM) (Aagaard et al., 2002a; Campos et al., 2002). Whilst utilising this type of training to develop maximum strength, the combination of volume and intensity may be enough to elicit acute neuromuscular fatigue. This fatigue may impact on subsequent training sessions performed by the athlete, either skill or capacity based, as observed by (Girard & Millet, 2008).

Whilst strength training is an important part of athletic preparation, other neuromuscular movements such as jumping and sprinting are also commonly trained to elicit improvements in athletic performance. Common examples of these are the CMJ, DJ, IMTP and 20-m sprint which have been used both as training tools, performance tests (Seitz et al., 2014; Viitasalo et al., 1998; Wang et al., 2016) and more recently as tools to monitor acute (Gathercole et al., 2015b; Hamilton, 2009a) and chronic (Gathercole et al., 2015b) neuromuscular fatigue. A number of factors are known to influence performance in these exercises such as time of day (Taylor et al., 2010) and strength levels. However only a small body of research has examined the effect of various fatigue generating stimuli on these type of tests (Cormack et al., 2008c; Gathercole et al., 2015a; Hamilton, 2009b).

Repeat high intensity running has been shown to diminish CMJ and DJ performance immediately, 24 h and 72 h later whilst 20-m sprint is only effected immediately afterwards (Gathercole et al., 2015a). In a sport specific context, fatigue generated from performing various sports has been shown to effect neuromuscular performance with an Australian rules football match resulting in reduced CMJ performance at least 24 h post-match (Cormack et al., 2008c). A competitive soccer match has also been shown to impair neuromuscular performance with CMJ diminished up to 69 h post-match whilst sprint performance (20 m) was only effected immediately post-match, recovering within 5 h (Andersson et al., 2008).

The effects of strength training protocols commonly used in athletic preparation on muscle activity and force development has shown various muscle activity patterns occur as a result of the fatigue generated from such training (Linnamo et al., 1997; McCaulley et al., 2009). However, this research used either the isometric squat or bilateral leg extension to monitor changes in performance. Whilst both tests have merit within a strength/power testing battery, they provide little insight into the effects of strength training on athletic ability as measured via more performance orientated tests such as the CMJ.

Other research examined the effect of strength training on neuromuscular performance and highlights that CMJ and DJ performance is affected by a high volume strength training session up to 72 h later (Byrne & Eston, 2002). This finding, whilst interesting, gives limited insight into typical athletic training program effects, due to the strength training protocol used (10 sets of 10 reps of the barbell squat at 70% 1RM) not being reflective of an athletic preparation session.

It is clear that limited research exists examining the effects of a typical maximum strength training program on acute neuromuscular fatigue in an athletic population. The primary aim of this study was to investigate the acute effects of a fatiguing maximum strength training session on common neuromuscular tests immediately, 4-, 24- and 48-h post. A secondary aim of this study was to compare these effects between athletes at different periods within the annual cycle to investigate variations in fatigue time course caused by adaptations to the predominant training focus.

5.3 Methods

Subjects

Following approval by the local ethics committee and in accordance with the declaration of Helsinki, 14 athletes from an elite sports academy were invited to participate in the study. All athletes (age 16.5 ± 1.1 y, height 171.3 ± 6.3 cm, body mass 65.0 ± 11.2 kg and 3RM Back Squat 82.6 ± 23.7 kg) received a clear explanation of the study, including risks and benefits of participation and provided written consent before the start of the study. Each subject had a minimum of two years resistance training history and was familiar with all of the tests used in the study.

Design

Athletes were assessed in a battery of neuromuscular tests over three training blocks, spanning an 18-week period within the annual cycle (Figure 5.1).

The 18-week period was divided into two periods, the ‘competition period’ and ‘preparation period’. During the competition period an average of one strength training session (Table 5.1a) per week (nine total sessions for the 9-week period) and five to six sport specific training sessions that included one speed and agility session and one conditioning session were performed. During the preparation period two to three strength training sessions (Table 5.1b) per week were performed (15 total sessions for the 6-week period) and five to six sport specific training sessions that included one to two speed and agility and conditioning sessions. Each testing block began with the athletes performing the neuromuscular test battery to determine baseline measures. After 24 h rest the athletes then performed a fatiguing maximum strength session before repeating the same neuromuscular test battery immediately post, 4-, 24- and 48-h post the strength session to assess the acute fitness vs fatigue state of the group.

Table 5.1. Strength training programs for competition (A) and preparation (B) periods

(A) Competition Period Exercises		(B) Preparation Period Exercises	
Day 1		Day 1	Day 2
Drop Jumps	3-4 sets of 4-6 reps	Back Squat	Deadlift
Countermovement Jumps	3-4 sets of 4-6 reps	Romanian Deadlift	Split Squat
Back Squat	3-4 sets of 4-6 reps	Single Leg Press	Leg Press
Bench Pull	3-4 sets of 4-6 reps	Bench Press	Decline Press
Dumbbell Press	3-4 sets of 4-6 reps	Bench Pull	Chin-Ups
Isometric Mid-Thigh Pull	2-3 sets of 3-6 s	Volume: 3-5* sets of 3-5 reps. Intensity: 85-91% 1 repetition max	

*Fifth set performed for Back squat or Deadlift only.

Figure 5.1. The 18-week training study period as a part of the yearly training plan for the subjects

January				February				March					April				May	
Preparation period 1				Competition period 1				Preparation period 2										
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18

* Weeks 1, 11 & 18 – denote testing weeks. Week 1 – block 1; week 11 – block 2; week 18 – block 3

Methodology

To minimise variability and limit the differing effects of one test upon another, the test battery was performed in the same order on each occasion. Before commencing the test battery, the athletes were required to perform a 10-minute, standardized dynamic warm-up which included dynamic running drills, dynamic stretches, two sets of three CMJ's (60% and 90% intensity), two, 25-m submaximal sprints (70% and 90% intensity) and one set of three DJ's (60%, 80% and 100% intensity). A minimum of three minutes rest was then given before the testing began. No additional dynamic warm-up was performed between the maximum strength session and the test battery immediately post. At the completion of the rest period, each subject completed the neuromuscular tests in the following order; three maximal CMJ's, three maximal DJ's from a 40 cm box, three maximal 20-m sprints and two maximal IMTP's. One minute rest was allowed between trials for the CMJ and DJ, two minutes rest was allowed between trials for the 20-m sprint and three minutes rest between trials for the IMTP. A minimum of two minutes rest was given as the subject moved from one neuromuscular test to the next. The exact testing procedures for these neuromuscular tests have been detailed previously and their respective reliability reported (Haines et al., 2016).

The maximum strength session was performed under the guidance of an experienced S&C coach. The strength session was designed to replicate a fatiguing maximum strength session whilst minimising variability from test block to test block. As such, one exercise was chosen, the back squat and each athlete performed 10 sets of 5 back squats at a starting weight of 85% 1RM, with three minutes rest between sets.

In the week before the testing blocks estimated 1RM back squat was determined for each subject. During the assessment the subjects were required to squat until their thighs were parallel with the floor. Squat depth was monitored visually by an experienced tester who observed all trials to ensure uniformity between subjects and testing blocks. Estimated 1RM was determined after specific warm-up sets were performed at 50% (five to eight repetitions), 70% (five repetitions) and 90% (one to three repetitions) of their previous known 3RM with their best set used to calculate estimated 1RM. A five minute rest period was allowed between efforts of 90% and above as previously described (Winchester et al., 2005).

Statistical Analysis

In order to assess if the time differences immediately, 4-, 24- and 48-h, post strength session for each test block were practically beneficial, trivial or harmful, the data were assessed using a magnitude based inferences approach. (Hopkins et al., 2009). Of interest was the magnitude of changes in CMJ, DJ, 20-m sprint and IMTP variables between baseline and each recovery time point, for the three test blocks. All analyses were performed using a modified statistical spreadsheet (Hopkins, 2006b) with data reported in text as means with standard deviations (SD) and figures as mean with 90% confidence intervals (CI). ES were calculated using 0.2 x between-athletes SD with the following threshold inferences used: ≤ 0.2 (trivial), > 0.2 (small), >0.6 moderate), >1.2 (large), >2.0 (very large) and >4.0 (extremely large) (Hopkins et al., 2009). These methods were selected because traditional statistical approaches often do not indicate the magnitude of an effect, which is typically more relevant to athletic performance than any statistically significant effect. A qualitative description of the differences was assessed with the chance the change/difference was a true effect evaluated as follows: 25-75% possibly; 75-95%, likely; 95-99%, very likely; > 99% almost certainly. If the 90% confidence intervals of the ES overlapped both ES small boundaries (0.2), then the changes were deemed unclear (Hopkins et al., 2009).

5.4 Results

A total of 10 subjects completed all neuromuscular tests in block 1 except for the IMTP (n=9). In block 2 a total of 7 subjects completed all the neuromuscular tests. A total of 10 subjects completed all neuromuscular tests in block 3 except for the 20-m sprint (n=9), where one athlete was withheld on medical advice from the academy doctor to recover from a minor calf strain. The varied subject numbers in the different test blocks were a result of either voluntary withdrawal from the study (n =2), a long-term injury that occurred external to the study (n = 1), or absence due to sporting competition. Mean ± SD data for selected test variables across all three tests blocks are reported in Table 5.2 (CMJ), Table 5.3 (DJ) and Table 5.4 (IMTP and 20-m sprint). All results are displayed as ES ± 90% CL with the true change likelihood also represented (%). Estimated 1RM performance varied across block 1 (90.2 ± 27.5 kg), block 2 (103.0 ± 33.5 kg) and block 3 (113.7 ± 28.0 kg), however a clear effect was only found between block 3 and block 1 (ES = 0.77 ± 0.23, 100%).

Table 5.2. Countermovement jump variables means ± SD for the three testing blocks

Variable	Block	Pre	IM Post	4 h post	24 h post	48 h post
Jump height (m)	1	0.41 ± 0.07	0.37 ± 0.06	0.40 ± 0.06	0.39 ± 0.07	0.41 ± 0.08
	2	0.42 ± 0.07	0.39 ± 0.05	0.42 ± 0.07	0.42 ± 0.07	0.44 ± 0.07
	3	0.43 ± 0.07	0.40 ± 0.06	0.42 ± 0.07	0.43 ± 0.06	0.43 ± 0.06
Relative peak power ($W.kg^{-1}$)	1	53.2 ± 5.3	49.2 ± 4.8	52.2 ± 5.1	52.2 ± 5.6	52.2 ± 7.0
	2	52.5 ± 5.8	49.7 ± 5.9	52.8 ± 5.1	53.8 ± 6.5	54.3 ± 5.7
	3	54.5 ± 5.4	52.0 ± 5.4	52.4 ± 5.3	53.9 ± 5.3	54 ± 5.3
Peak concentric force (N)	1	1626 ± 285	1514 ± 262	1617 ± 273	1616 ± 308	1650 ± 358
	2	1755 ± 347	1622 ± 265	1803 ± 382	1703 ± 414	1705 ± 368
	3	1777 ± 349	1648 ± 252	1731 ± 309	1687 ± 342	1715 ± 361
Eccentric : Concentric Ratio	1	223.3 ± 41.2	214.8 ± 42.8	210.3 ± 41.1	213 ± 33.6	206.4 ± 40.3
	2	214.8 ± 34.5	215.4 ± 34.0	213.2 ± 38.5	213 ± 36.2	203.6 ± 24.5
	3	228.1 ± 32.8	236.6 ± 45.3	221.6 ± 39.9	214.2 ± 29.6	228.5 ± 28.4

Table 5.3. Drop jump variables means ± SD for the three testing blocks

Variable	Block	Pre	IM Post	4 h post	24 h post	48 h post
Jump height (m)	1	0.30 ± 0.07	0.25 ± 0.04	0.29 ± 0.07	0.24 ± 0.06	0.26 ± 0.07
	2	0.25 ± 0.05	0.20 ± 0.06	0.24 ± 0.04	0.25 ± 0.04	0.26 ± 0.04
	3	0.25 ± 0.06	0.22 ± 0.05	0.24 ± 0.03	0.24 ± 0.05	0.23 ± 0.05
Relative peak power ($W.kg^{-1}$)	1	64.1 ± 10.9	54.8 ± 7.3	64.2 ± 14.8	54.3 ± 12.2	60.8 ± 16.5
	2	61.1 ± 10.3	49.0 ± 14.7	56.5 ± 10.7	57.6 ± 10.9	60.5 ± 12.0
	3	57.6 ± 10.2	52.2 ± 9.6	59.4 ± 9.2	57.8 ± 11.5	59.7 ± 12.2
Reactive strength index ($m.s^{-1}$)	1	1.32 ± 0.30	1.05 ± 0.21	1.32 ± 0.40	1.01 ± 0.33	1.23 ± 0.36
	2	1.20 ± 0.29	0.89 ± 0.37	1.10 ± 0.28	1.10 ± 0.30	1.20 ±0.36
	3	1.11 ± 0.30	0.99 ± 0.26	1.16 ± 0.25	1.11 ± 0.31	1.14 ± 0.30

Table 5.4. IMTP and 20m sprint variables means ± SD for the three testing blocks

Variable	Block	Pre	IM Post	4 h post	24 h post	48 h post
Peak force (N)	1	2208 ± 555	2425 ± 484	2558 ± 584	2659 ± 569	2748 ± 597
	2	2529 ± 516	2425 ± 496	2600 ± 633	2585 ± 546	2605 ± 562
	3	2549 ± 519	2413 ± 377	2563 ± 455	2578 ± 487	2535 ± 428
Relative peak force (N/kg)	1	3.32 ± 0.34	3.64 ± 0.25	3.81 ± 0.37	4.00 ± 0.42	4.13 ± 0.43
	2	3.73 ± 0.31	3.57 ± 0.34	3.77 ± 0.41	3.77 ± 0.30	3.78 ± 0.23
	3	3.80 ± 0.51	3.62 ± 0.43	3.82 ± 0.44	3.84 ± 0.52	3.79 ± 0.46
5-m split time (s)	1	1.13 ± 0.10	1.09 ± 0.06	1.05 ± 0.06	1.08 ± 0.07	1.07 ± 0.08
	2	1.07 ± 0.06	1.14 ± 0.09	1.15 ± 0.06	1.14 ± 0.07	1.16 ± 0.08
	3	1.10 ± 0.07	1.10 ± 0.07	1.09 ± 0.06	1.08 ± 0.06	1.06 ± 0.05
20-m split time (s)	1	3.22 ± 0.20	3.22 ± 0.15	3.17 ± 0.15	3.19 ± 0.17	3.17 ± 0.17
	2	3.14 ± 0.17	3.25 ± 0.18	3.21 ± 0.16	3.20 ± 0.15	3.23 ± 0.17
	3	3.12 ± 0.14	3.19 ± 0.18	3.12 ± 0.13	3.10 ± 0.13	3.08 ± 0.13

Neuromuscular performance

Small effects were seen on a number of CMJ performance variables across the various blocks and time points (Figure 5.2). Immediately post strength session showed the most susceptibility to variations in performance with jump height (ES ± block 1 -0.44 ± 0.29, 92%; block 2 -0.45 ± 0.19, 99%; block 3 -0.38 ± 0.14, 98%), relative peak power (block 2 -0.44 ± 0.21, 96%; block 3 -0.45 ± 0.17, 93%) and peak concentric force (block 1 -0.38 ± 0.21, 92%; block 2 -0.32 ± 0.18, 88%; block 3 -0.31 ± 0.28, 75%) all being likely or very likely reduced. Relative peak power was also very likely reduced (-0.70 ± 0.32, 99%) immediately post strength training during block 1. Technique based changes were seen at a greater number of time points such as eccentric to concentric ratio in block 1 which showed a likely reduction (-0.42 ± 0.10, 58%) relative to baseline up to 48 h post strength session.

DJ exhibited greater variation and magnitude in response to a maximum strength session (Figure 5.3). Jump height showed moderate reductions immediately post strength training for both block 1 (-0.65 ± 0.30, 99%) and block 2 (-1.15 ± 0.56, 99%) and also 24-h and 48-h post during block 1 (-0.72 ± 0.67, 90% and -0.61 ± 0.63, 87%). RSI showed a moderate reduction immediately and 24-h post strength session within block 1 (-0.77 ± ; 100% and -1.01 ± ; 96%) and a large reduction immediately post strength session during block 2 (-1.47 ± 0.91, 98%). Other small reductions were noted at various time points within each block.

Peak force measured via the IMTP was improved during block 1 with small effects noted immediately post- (0.39 ± 0.20, 94%), 4-h post (0.58 ± 0.15, 100%) and moderate effects 24-h (0.73 ± 0.90, 100%) and 48-h post (0.85 ± 0.19, 100%). Relative peak force showed a similar, with greater magnitude, trend across all time points during block 1 (0.85 ± 0.47, 98%, 1.23 ± 0.37, 100%, 1.64 ± 0.39, 100% and 1.93 ± 0.44, 100%) however it also showed a small decrease immediately post strength session for both blocks 2 (-0.49 ± 0.58, 81%) and 3 (-0.31 ± 0.35, 70%).

Within the 20-m sprint the 5-m split showed moderate increases at every time point for block 2. In contrast block 1 experienced a small reduction immediately (-0.37 ± 0.33, 82%), 24- (-0.4 ± 0.35, 84%) and 48-h (-0.53 ± 0.37, 93%) post and moderate reduction 4-h (-0.68 ± 0.33, 99%) post the strength session. Block 3 experienced a small reduction in 5-m split 24- (-0.27 ± 0.32, 66%) and 48-h (-0.51 ± 0.32, 94%) post strength training. Small increases in 20-m split time were seen during block 2 at all recovery time points whilst small reductions were seen 4- and 48-h post training in block 1 (-0.21 ± 0.23, 53%; -0.22 ± 0.23, 56%). Block 3 showed the most interesting pattern with a small increase in 20-m split immediately post training (0.47 ± 0.48, 84%) and a small reduction in time 48-h post (-0.25 ± 0.13, 73%) as shown in Figure 5.4.

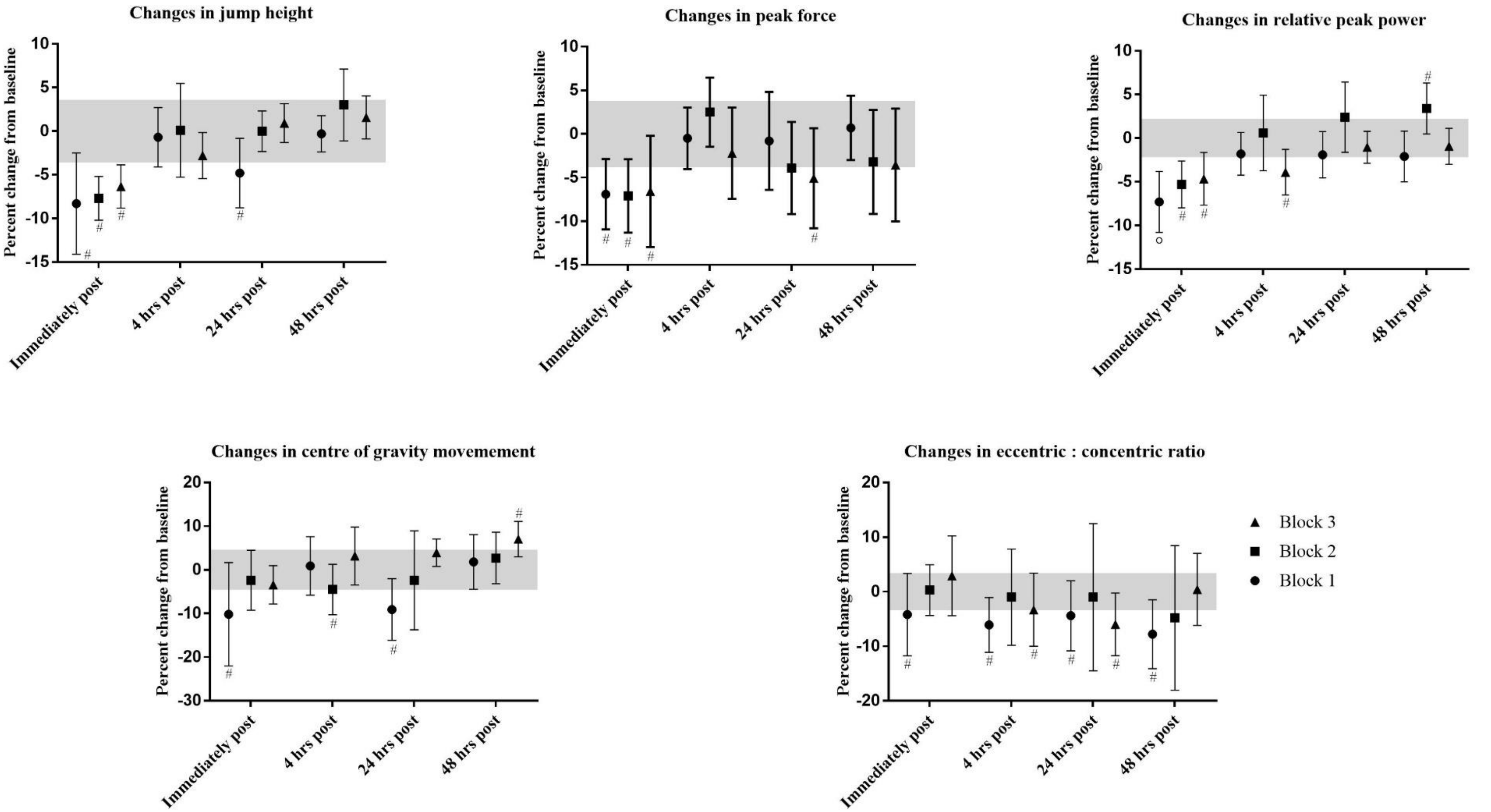

Figure 5.2. Changes in CMJ variables post strength session across the three different testing periods. The trivial effect (ES = 0.2) thresholds are presented as a percentage for each variable as the grey shaded area. # = small effect size, ° = moderate effect size

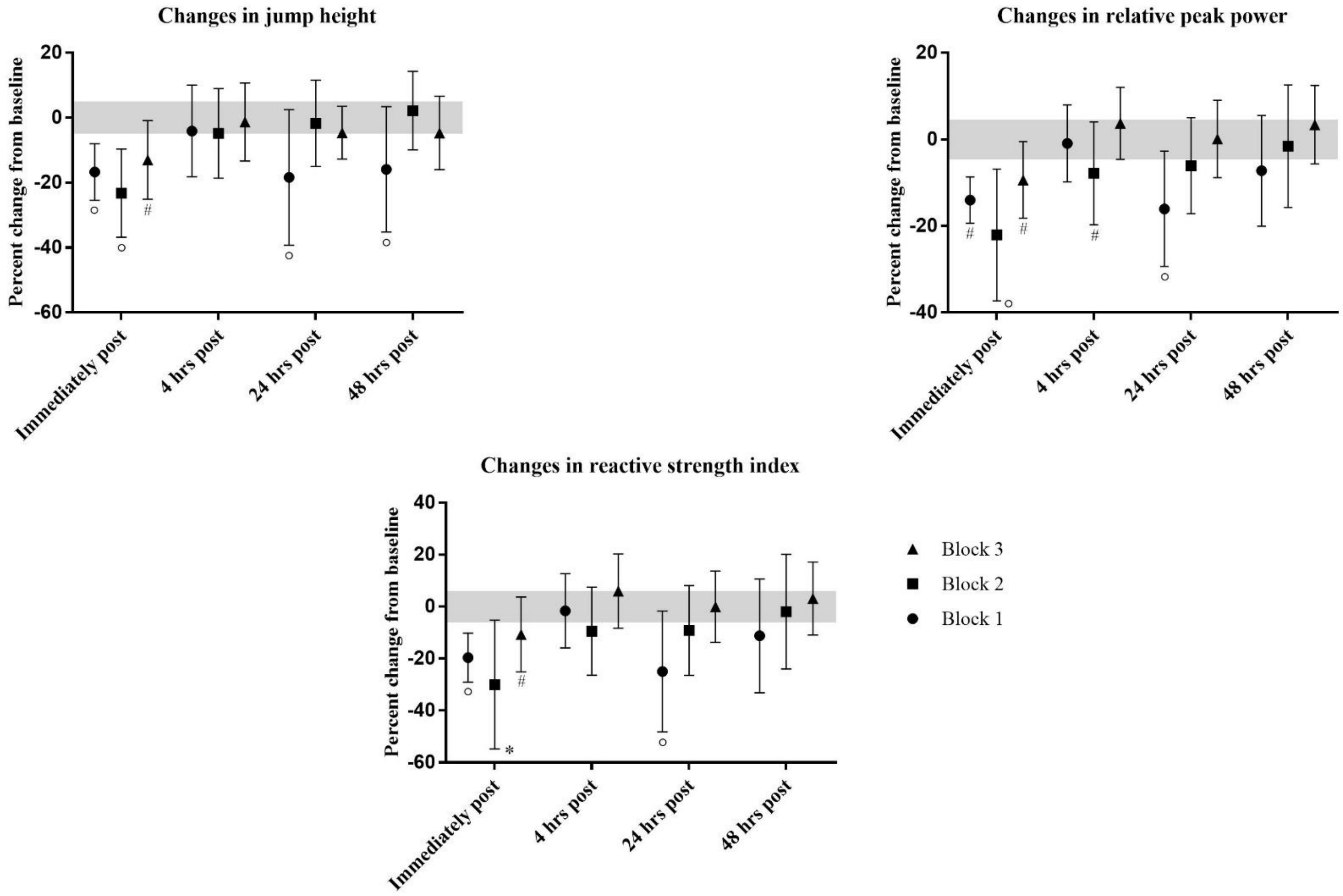

Figure 5.3. Changes in drop jump variables post strength session across the three different testing periods. The trivial effect (ES = 0.2) thresholds are presented as a percentage for each variable as the grey shaded area. # = small effect size, ° = moderate effect size, * = large effect size

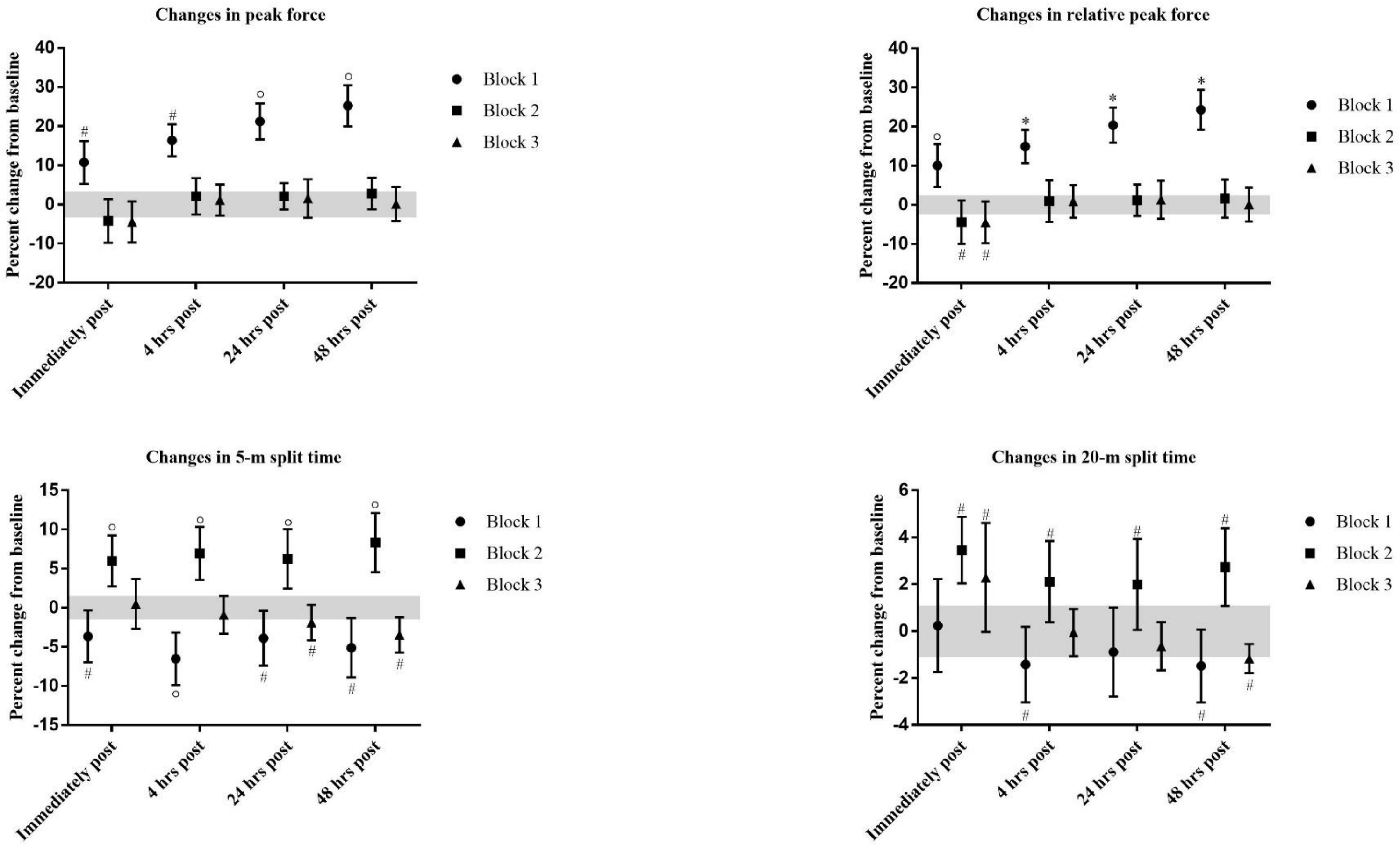

Figure 5.4. Changes in isometric mid-thigh pull and 20 m sprint variables post strength session across the three different testing periods. The trivial effect (ES = 0.2) thresholds are presented as a percentage for each variable as the grey shaded area. # = small effect size, ° = moderate effect size, * = large effect size

5.5 Discussion

The present study investigated how a fatiguing maximum strength session affected CMJ, DJ, IMTP and 20-m sprint at multiple time points across 48 h in three different periods within the annual training cycle of adolescent athletes. The key findings were that; 1) select neuromuscular tests exhibit different recovery profiles over a 48 h period and therefore will benefit from appropriate scheduling within the weekly training cycle, 2) the DJ may be the most sensitive test for detecting neuromuscular fatigue in adolescent athletes, 3) athletes displaying higher levels of back squat strength (block 3) may be less susceptible to neuromuscular fatigue generated via maximum strength training sessions when assessed by the 20-m sprint.

Jumping performance was most effected immediately post a fatiguing maximum strength session as indicated by the harmful effects seen in multiple variables for CMJ (Figure 5.2) and DJ (Figure 5.3). Decreases in common performance variables such as jump height, relative peak power and peak force for CMJ and jump height, RSI and relative peak power for DJ highlight that these exercises whether used as tests or training tools should not be performed when high levels of neuromuscular fatigue exist. However, the CMJ showed that from 4 h post session onward, minimal performance effects (harmful or beneficial) will be experienced if is utilised as training exercise. When examining fatigued CMJ performance, previous research (Gathercole et al., 2015b) has highlighted the need to include technique-based variables in the analysis due to differing effects when compared with performance variables only. The current data (Figure 5.2) suggests that changes in technique, as indicated by a reduction in the eccentric: concentric ratio, may exist at least 48 h post a fatiguing strength session in weaker athletes (block 1) with effects not lasting as long in stronger athletes (block 3).

As mentioned above, DJ performance showed harmful performance effects immediately after the strength session however in comparison to the CMJ, these effects were of greater magnitude with some variables showing moderate (jump height and relative peak power) and even large (RSI) harmful effects immediately post session. Additionally, the effects appeared to be longer lasting with DJ performance effected for at least 48 h for jump height, relative peak power and RSI (Figure 5.3). Specifically, both block 1 and block 2 showed small to moderate harmful effects 24 h post in multiple variables. However, as with the CMJ this was only found in the weaker groups with the strongest group (block 3) showing no clear harmful performance effects at any time point other than immediately post. The increased magnitude and duration of harmful performance effects may be explained by the shorter available contraction time used when performing a DJ compared with a CMJ.

This is similar to results reported by Gathercole et al, (2015a) however in their study, whilst magnitude of effects immediately post a fatiguing session where higher in the DJ when compared with a CMJ, the effects were longer lasting in the CMJ. It is important to note that the fatigue generating sessions used were different in these studies, with the subjects exposed to repeat high intensity running instead of the maximum strength training session used in the current study which may affect fatigue profiles. Previous literature also found the fatigue generated from a soccer match to have a negative effect on RSI measured via the DJ, again highlighting the usefulness of this test in detecting changes in performance after various stimuli (Hamilton, 2009a).

Within the IMTP, minimal effects of fatigue were seen during block 2 and block 3 (Figure 5.4) with only relative peak force showing likely and possibly small harmful effects (-0.49 and -0.31) immediately post session, with no clear effects seen in peak force. In contrast, in block 1 athletes showed small to moderate beneficial effects in peak force and moderate to large beneficial effects in relative peak force. The authors contend that rather than a 'true' effect of the fatiguing strength session (block 1), the trend of the magnitude of effect for both variables indicate that the athletes where improving from test to test. This is inconsistent with the results seen in blocks 2 and 3. The authors' postulate that the familiarisation block, whilst focussing on correct set-up and technique may not have fully recreated the intent for the athlete to perform the exercise with a maximal effort. The data suggests that the athletes were not 'test familiar' with the IMTP until the beginning of block 2. It is however interesting to note that the performance recorded for either peak force or relative peak force 24-h and 48-h post in block 1 were higher than at any other time points during the study (Table 5.1).

In the 20-m sprint differing fatigue related time courses were seen across the 3 blocks (Figure 5.4). During blocks 1 and 3 the only harmful effect seen at any time point was a likely small effect (0.47) immediately post. Block 1 consistently showed small to moderate, likely or very likely beneficial effects on 5-m sprint time (all time points) and also showed possibly small beneficial effects on 20-m sprint time 4- and 48 h post (Figure 5.4). This result is somewhat surprising as it could be expected that there would be a harmful effect on sprint performance as seen in other literature (Gathercole et al., 2015a). The current results may simply reflect the period during which block 1 was performed, that is prior to the athletes having completed any significant sprint training during the annual cycle and therefore recording their slowest sprint times from all three blocks (Table 5.3). That is, accumulated fatigue may not have been sufficient to decrease performance any lower than the athletes were already capable of. Interestingly, both 5-m and 20-m performance appeared to show a specific trend in fatigue recovery during block 3. The 5-m split showed a trend towards improved performance over time with both 24- and 48-h post showing possibly and likely effects (-0.27 and -0.51), respectively. A similar, yet more pronounced trend was seen in 20-m performance with a likely small harmful effect seen immediately post, trivial effects at 4- (-0.01) and 24-h (-0.13) post and a possibly small beneficial effect (-0.24) seen 48 h post. These results suggest that adolescent athletes who have obtained higher levels of strength (block 3) as measured in the back squat and have potentially greater tolerance to a lower body strength session due to completing a specific strength block, may exhibit delayed potentiating effects on sprint performance. In contrast, block 2 showed either likely or very likely harmful effects for both 5-m (moderate effect) and 20-m (small effect) splits at all the recovery time points. As with block 1 this may in part be due to the specific timing with the annual cycle and the preceding training block. Block 2 was performed at the end of a competition period where a much lower training volume had been completed. Although athletes showed good baseline performance in 5-m and 20-m variables (Table 5.3) the lack of tolerance to strength training may have resulted in significant fatigue being accumulated during the strength session subsequently effecting performance at all measured recovery time points.

Results of this study showed that a maximum strength training session produced an immediate fatigue that dissipated over time. The data shows that performance in the neuromuscular assessments used in this study, irrespective of whether they are used as training exercises or as a monitoring tool, may be affected at different time-courses post a strength session such as the one used in the current this study. Consequently, S&C coaches should consider these fatigue related effects planning their athletes training schedule. Whilst the findings from the current study suggest multiple effects as a result of the training, they must be interpreted with caution due to the low subject numbers assessed. The authors' also note that due to the small sample of athletes combined with the range of physical qualities present in adolescent athletes, many results displayed large confidence intervals, potentially resulting in unclear results. This does however highlight the occurrence of individual responses to fatigue generation and the need to determine individual responses when working with elite athletes.

5.6 Conclusion and Practical Applications

The present study highlights the various neuromuscular fatigue patterns that occur after performing a fatiguing maximum strength session at different time periods in the annual cycle. In practice, these different neuromuscular fatigue recovery profiles indicate that specific training should be planned to maximise an athlete's readiness to perform such training. For example, if a maximum strength session is performed in the morning, CMJ training may be performed as early as that same afternoon whereas DJ training should be avoided for at least 24 h. As peak force was found to return to baseline as measured in the IMTP 4-h post training, it may be possible to perform a subsequent maximum strength session at such a time. However, importantly such a session should be similar in nature involving similar muscle contraction patterns and ranges given the specific nature of the IMTP. Similarly, the 20-m sprint may also be trained 4 h post a strength session. Importantly, practitioners should consider what period within the annual cycle the athlete currently sits, specifically what training the athlete has completed over the previous 6 weeks and what tolerance to fatigue they currently possess. That is, as shown in the current study, athletes that have performed a 6-wk maximum strength training block may better tolerate a maximum strength training session.

Chapter 6

Longitudinal neuromuscular monitoring tool: A case study using bodyweight vs loaded countermovement jump

Haines, B., & Deakin, G. (2014). Longitudinal neuromuscular monitoring tool: A case study using bodyweight vs loaded countermovement jump. *Journal of Australian Strength and Conditioning, 22*(5), 37-40

Due to relocating from Qatar to Australia at the completion of study 3 (Chapter 5), the subject group available for assessment changed. As such, the focus of this study shifted from adolescent to adult athletes with the aim of comparing the effectiveness of both a CMJ_{BW} and CMJ_{LOAD} to longitudinally monitor neuromuscular readiness in adult athletes. Although this study has been published in a peer-reviewed journal, the abbreviations BWCMJ and LCMJ have been replaced with CMJ_{BW} and CMJ_{LOAD} respectively to ensure continuity throughout this thesis.

This chapter is an extension of the research presented in Chapter 5 and was designed to investigate simple neuromuscular assessments that can potentially be used to assess neuromuscular fatigue in response to strength training in an adult athlete population. The previously used test battery of CMJ, DJ, IMTP and 20-m sprint could not be used with the cohort of adult athletes available for this study and as such, simplified tests which were familiar to the athletes were used. This resulted in the selection of two different load CMJ's to be assessed in this study. This study presents rare longitudinal data (23 weeks) collected on an elite athlete.

6.1 Abstract

Purpose: To examine the effectiveness of both the BWCMJ and LCMJ in monitoring neuromuscular readiness in an elite athlete during an extensive training block. **Methods:** An elite, male beach volleyball player (height = 191 cm, weight = 95.6 kg, age = 25 y, back squat 1RM = 200 kg) performed three BWCMJ and three LCMJ weekly during a 23-week training block.

Changes in performance were compared against baseline data collected prior to the training period and reported as percent change from baseline. **Results:** Both BWCMJ and LCMJ showed sensitivity to neuromuscular fatigue over the period, however BWCMJ was more effective at determining the effects of the competition taper than LCMJ. **Conclusion:** Relative peak power was able to detect varying levels of neuromuscular fatigue throughout the study period however when measured via either the BWCMJ or LCMJ however during the taper period, only the BWCMJ was able to effectively determine the improved neuromuscular performance.

6.2 Introduction

Monitoring neuromuscular readiness in athletes has been a topic of scientific and applied interest recently, the benefit, allowing the practitioner to monitor the effect of training interventions on the physiological readiness of their athlete both acutely and longitudinally throughout a training and competitive season. The ability to monitor the acute neuromuscular readiness of an athlete via a CMJ has previously been established in the literature (Cormack et al., 2008a; Cormack et al., 2008c; Taylor et al., 2010). Some research has examined the use of BWCMJ (Cormack et al., 2008c) whilst others have examined LCMJ (Taylor et al., 2010). A number of variables have been investigated in the literature with researchers examining force, power and displacement measures from absolute, relative, peak and mean variations. Taylor (2010) previously reported that peak force and relative peak power were 'good' variable measures to use due to the inter-day test reliability (Taylor et al., 2010). However, to date the majority of research has focused on larger team sports (Andersson et al., 2008; Cormack et al., 2008a; Cormack et al., 2008c; Ronglan et al., 2006; Spiteri et al., 2013). In determining an effective load to be used in a LCMJ previous research has found that an additional CMJ load of as little as 27% 1RM back squat may alter performance variables such as relative peak power (Cormie, McCaulley, Triplett, & McBride, 2007b). In selecting an appropriate load for a LCMJ assessment tool, it may be prudent to use a load that elicits a different performance result to a BWCMJ, but that minimises any risk to the athlete by placing a large external load across their shoulders when jumping. To the authors knowledge no research has monitored the neuromuscular readiness of an elite beach volleyball athlete or has examined if any difference in response is observed between a BWCMJ or LCMJ. The purpose of this case study was to examine the efficacy of using a BWCMJ or LCMJ to monitor neuromuscular readiness throughout a preparation period for an elite beach volleyball athlete.

6.3 Methods

To investigate the differences between a BWCMJ and a LCMJ as a neuromuscular monitoring tool, an elite male beach volleyball athlete was tested once per week over a period of twenty-three weeks (May 2013 – October 2013). The subject (height = 191 cm, weight = 95.6 kg, age = 25 y, back squat 1RM = 200 kg) was a member of the Australian beach volleyball program with over seven years' experience as a national team member and more than nine years strength training experience. For the duration of the case study he was preparing for an international competition, performing strength training three times per week in addition to his on-sand training which varied during the monitoring period. The subject received a clear explanation of the study, including risks and benefits of participation and provided written consent before the start of the study. The study was approved by the James Cook University Human Ethics Committee. Strength training sessions focused primarily on the lower body, however most sessions contained some upper body and trunk strengthening exercises. Training volume and intensity across the analysis period for the lower body is presented in Table 6.1.

Both a BWCMJ and LCMJ equal to 30% of the subject's 1RM back squat (60 kg) were tested at the same approximate time each Monday morning during the athlete's first training session for the week. The athlete performed his normal warm-up consisting of a five minute general dynamic warm-up, concluding with three submaximal BWCMJ's and LCMJ's before completing three maximal BWCMJ's and three maximal LCMJ's on a portable force plate (AMTI, Frappier Acceleration, USA). To maintain a similar jumping technique and allow for comparison between the two types of jumps, a wooden broom stick (approx. 0.7 kg) was used for each BWCMJ. The countermovement used for each jump was self-selected by the athlete and a minimum of 30 s rest was given between each jump, with a minimum of two minutes rest given between the BWCMJ and LCMJ. Data was collected using DartPower software version 1.6 at a sampling frequency of 200 Hz and analysed using custom-designed software using the impulse momentum approach as described by Dugan et al. (Dugan et al., 2004). A fourth-order, low-pass Butterworth digital filter with a cut-off frequency of 10Hz was used to filter and smooth the data. The only cue given to the athlete was to maximize jump height, as such the best trial for analysis was selected on the jump that elicited the highest jump height. The variables chosen to monitor neuromuscular fatigue were peak force (N) and relative peak power (W/kg^{-1}) with body mass (kg) changes also displayed. Additionally, this protocol was performed in the four-weeks preceding the monitoring period during which a return to strength-training program was performed. The subsequent values were averaged to create baseline values.

Table 6.1. Training load distribution across the monitoring period

	Max strength		High load power 1		High load power 2		Repeat Power		Low load power		Taper	
	Volume	Intensity	Volume	Intensity	Volume	Intensity	Volume	Intensity	Volume	Intensity	Volume	Intensity
CMJ_{BW}			67						105		84	
CMJ_{LOAD}			128	40-50%	168	50-70%	720	30-50%	51	30-50%	51	30-50%
Power clean	46	60-80%	72	85-105%	96	75-105%			36	30%		
Clean pull							228	50-70%				
LB force	124	80-95%			50	80-90%						

Volume presented as total reps per program phase, intensity range presented as percentage of 1RM. *LB = lower body force exercise (back squat, box squat and trap bar deadlift). CMJ_{BW} = Bodyweight countermovement jump. CMJ_{LOAD} = Loaded countermovement jump.

6.4 Results

Changes in body mass over the monitoring period are shown in Figure 6.1.

When considering relative peak power, both types of BWCMJ and LCMJ showed sensitivity to varying levels of neuromuscular fatigue (Figure 6.2) with similar trends throughout the monitoring period. The only major difference appeared during weeks 2 and 3 of the taper period when relative peak power in the BWCMJ increased to its highest levels of the monitoring period (+6.0%) and remained high (+5.3%) whilst relative peak power in the LCMJ remained at baseline (-0.2%) before decreasing (-3.6%). Both measures also showed good sensitivity to the high levels of strength training volume and intensity that occurred during the repeat power mesocycle with both BWCMJ and LCMJ showing their biggest decrements from baseline with -7.9% and -8.7% respectively after the high volume of power endurance week 3.

In contrast, peak force from the two jump types showed varying impacts of neuromuscular readiness for the majority of the study (Figure 6.3) with only the last four weeks showing any similarity in results. Additionally, BWCMJ peak force appeared to be a less consistent measure throughout the period.

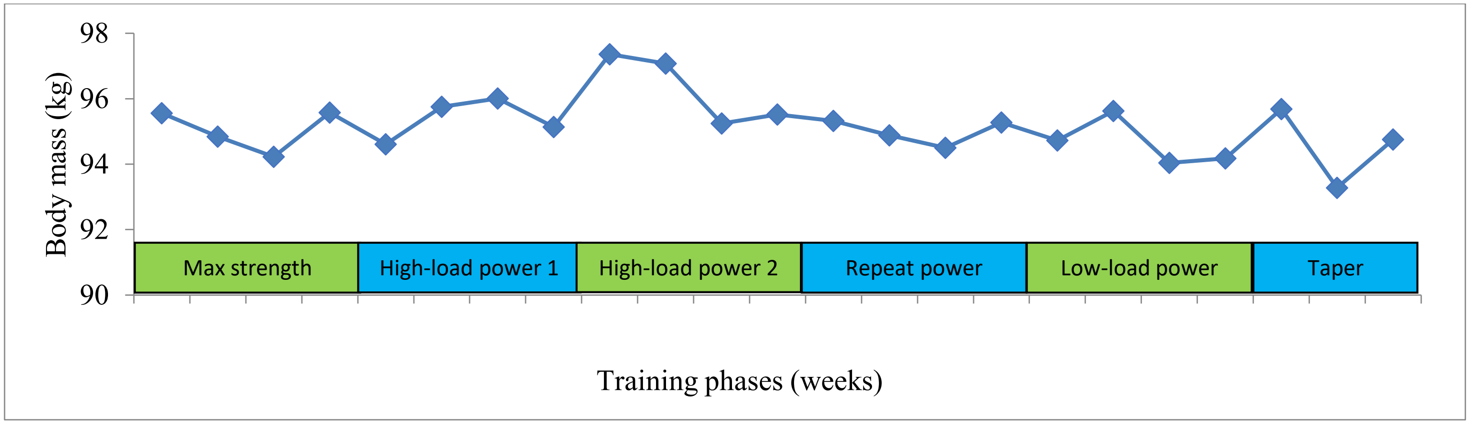

Figure 6.1. Changes in body mass (kg) over the monitoring period (weeks)

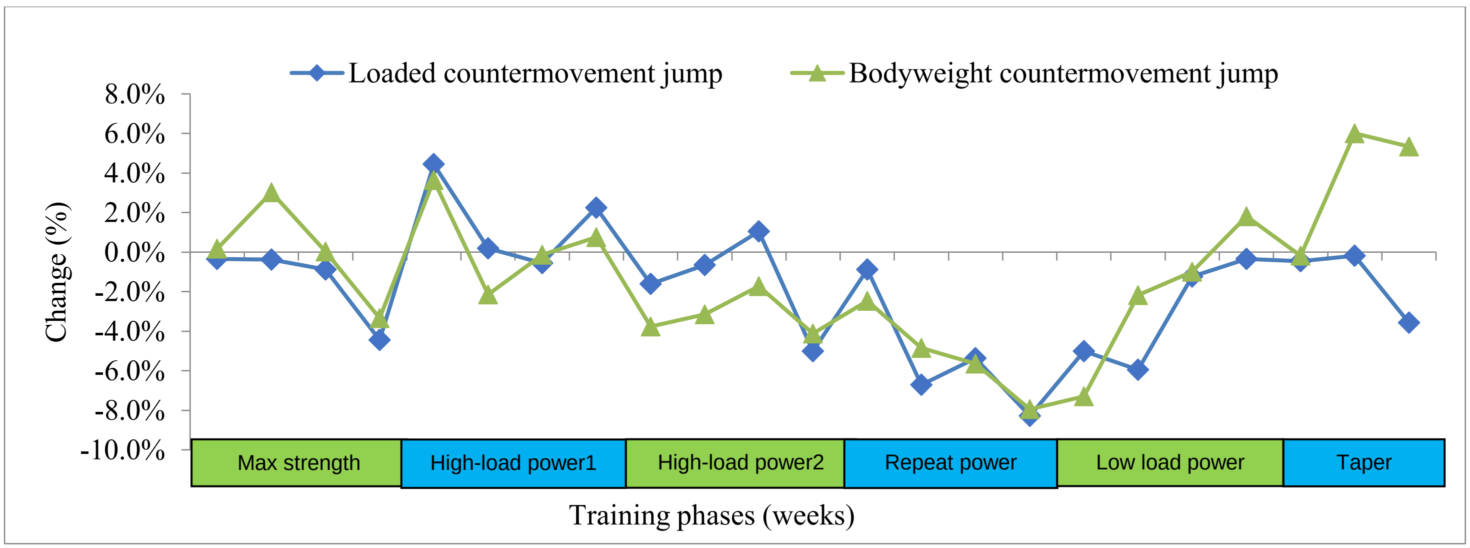

Figure 6.2. Percentage change in relative peak power (W/kg^{-1}) for bodyweight countermovement jump and loaded countermovement jump for relative peak power ($W.kg^{-1}$).

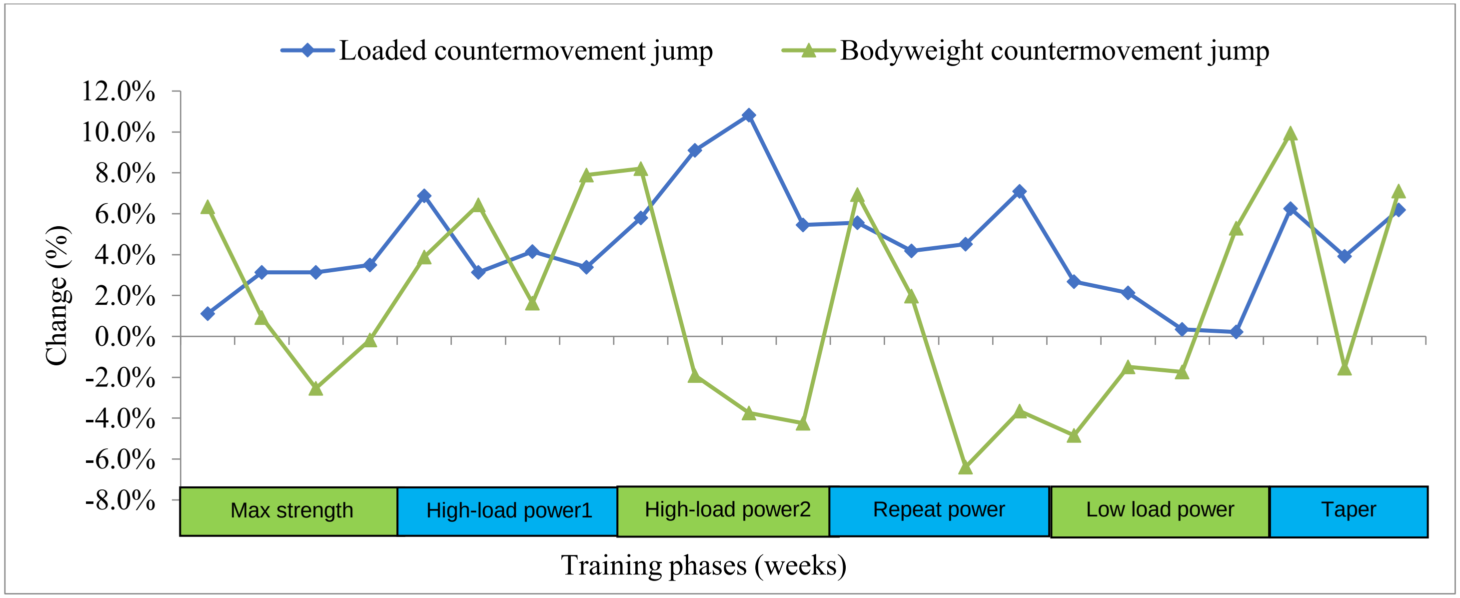

Figure 6.3. Percentage change in peak force (N) for bodyweight countermovement jump and loaded countermovement jump.

6.5 Discussion

The findings from this case study indicate that relative peak power when measured via a BWCMJ or LCMJ may be sensitive to neuromuscular fatigue in an elite beach volleyball athlete for the majority of a training season. However, attention should be paid when monitoring during tapering periods as reductions may be seen in LCMJ relative peak power compared to improvements in BWCMJ. In this case the decrement seen was most likely due to a reduction in high force strength training activities during the low load power and taper weeks.

The data also suggests that peak force measured via either a BWCMJ or LCMJ is not an accurate measure of neuromuscular fatigue for this athlete. Additionally, it suggests that the specificity of training may play a large role on the amount of force that can be expressed in a similar power movement. That is, peak force in the LCMJ increased throughout the monitoring period whilst high force exercises, either maximal or explosive, were being performed and peaked in week three of the high-load power 2 phase. This then stabilized whilst severe fatigue was accumulated during the power endurance phase and then returned to baseline levels during the low-load power training period with a final peak during the taper period.

The large differences in peak force responses during the monitoring period between the BWCMJ and LCMJ could be due to the longer contraction time experienced during the LCMJ. The increased contraction time could allow fatigued muscles the time to produce peak force that is otherwise not possible during a shorter contraction type as seen in the BWCMJ.

6.6 Practical applications

When considering an appropriate test and the variables within to monitor neuromuscular fatigue longitudinally then applied practitioners should consider using the BWCMJ with relative peak power as the more appropriate monitoring tool than peak force. Day of testing, time of testing and volume/intensity of exercise preceding the test day should also be standardized as much as possible to provide consistency in the testing environment and aid reliability.

Chapter 7

Changes in jump performance of endurance vs strength athletes during a maximum strength and maximal power resistance training block

Haines, B., Bourdon, P., Stanley, J., & Deakin, G. (Submitted). Changes in jump performance of endurance vs strength athletes during a maximum strength and maximal power resistance training block. *International Journal of Sports Physiology and Performance*

In follow-up to the findings on adaptations of adolescent athletes reported in Chapter 4, the authors wanted to perform a similar investigation on adult athletes. Due to the change in testing equipment available after the principal author's relocation and the limited time available for performing assessments on elite level athletes, the test battery was simplified. In order to keep continuity with the preceding chapter, the authors chose the tests used in chapter 6 (CMJ_{BW} and CMJ_{LOAD}) to assess changes across the training periods. Four-week strength or power training blocks were chosen to reflect a 'typical' training mesocycle utilised with adult athletes.

7.1 Abstract

Purpose: To compare the responses of endurance (END) or strength (STR) based athletes to a maximum strength (MS) and maximum power (MP) resistance training program. **Methods:** Ten athletes completed a 4-week MS and 4-week MP resistance program with weekly monitoring of neuromuscular performance. **Results:** During a MS block bodyweight countermovement jump (CMJ_{BW}) relative peak power (7.8% ± 4.8%) and loaded countermovement jump (CMJ_{LOAD}) relative peak power (5.9% ± 8.3%) and jump height (8.4% ± 8.5%) exhibited greater changes for STR vs END athletes. A MP block resulted in CMJ_{BW} relative peak power (9.8% ± 8.6%), jump height (8.0% ±6.4%), CMJ_{LOAD} relative peak power (7.0% ± 5.7%) and jump height (5.2% ± 4.6%) increasing more for STR vs END athletes. Jump technique varied in effect direction for the LCMJ, having a larger positive effect during a MS block and a larger negative effect during a MP block for STR vs END athletes. **Conclusion:** STR athletes showed consistently greater improvements in performance variables for both CMJ_{BW} and CMJ_{LOAD} during either a MS or MP block when compared with the changes seen in END athletes. In the CMJ_{BW} this is due to changes

in neuromuscular performance as opposed to a change in technique. Within the CMJ_{LOAD}, although changes in technique are apparent, these are not consistent with concurrent performance variable changes.

7.2 Introduction

Resistance training is commonly used as a method to enhance performance in a multitude of sports (Baker, 2001; Beattie et al., 2016; Bennie & Hrysomallis, 2005; Christou et al., 2006; Haines & Deakin, 2014; Harries et al., 2016; Hoffman et al., 2005; Howatson et al., 2016). These resistance training programs typically focus on two main qualities that underpin general sporting task performance (Suchomel et al., 2016). First, strength which can be described as the muscles ability to exert force on an external object (Stone, 1993) and second, power or 'explosive' muscle strength, commonly defined as the rate of rise in contractile force (Aagaard et al., 2002a). In an applied setting, external mechanical power as measured by the output of general sport characteristics such as jumping or sprint is more commonly of interest due to its direct impact on sport performance (Suchomel et al., 2016) and as such is a frequently used test to monitor increases in performance (Cormie et al., 2010; Rønnestad et al., 2012; Sheppard et al., 2008b).

Adaptations to both maximum strength (MS) or maximum power (MP) training in different athletes, has not been extensively researched. Previous literature has focussed on either athletes of different level responses within a sport, (Baker, 2001; Beattie et al., 2016; Dasteridis et al., 2011), or examining the strength/power ability of athletes from differing sporting backgrounds at a specific time-point (Asçi & Açikada, 2007; Izquierdo et al., 2004; McBride et al., 1999). Whilst this information provides useful data within each specific sport, it does not contribute to the general understanding of how athletes from different sporting backgrounds may respond to similar resistance training programs. For example, athletes from a strength/power based background may show different responses to either a MS or MP program when compared with endurance athletes. Consequently, assumptions on MS or MP training block outcomes may be erroneous if the specific population group performing the training stimuli is not accounted for. Hakkinen and Keskinen (Häkkinen & Keskinen, 1989) demonstrated that endurance and strength/power based athletes exhibited different maximal force characteristics in both absolute and relative to muscle CSA and different maximal RFD. They postulated that the highly specific stimuli of either strength/power training or endurance training over a very long period of time may result in differences in neural activation to the muscle and/or characteristics of the muscle tissue itself. Based on these findings it is reasonable to assume that endurance (END) athletes, characterised by a high volume of low resistance, long duration exercise will respond differently to various resistance training programs compared with strength/power athletes (STR), characterised by a low volume of high resistance, short duration exercise. (Häkkinen & Keskinen, 1989).

Several performance tests are commonly used in athletic testing to monitor the effects of a training stimulus on neuromuscular performance (Gathercole et al., 2015a; Gathercole et al., 2015b; Kyröläinen et al., 2005; Raeder et al., 2015; Wang et al., 2016). A test that has high reliability, the precision to detect changes and is familiar to most athletes given its ease of execution is the CMJ (Gathercole et al., 2015a; Raeder et al., 2015; Sheppard et al., 2008b). However, it has been recently proposed that the use of a two-load method in assessing changes in force-velocity profiles may give additional insight into performance changes (Jaric, 2016). Similarly, previous research has shown that the addition of load to a CMJ as little as 27% 1RM back squat may alter performance in key variables such as relative peak power (Cormie et al., 2007b). Therefore, the use of a bodyweight CMJ (CMJ_{BW}) and loaded CMJ (CMJ_{LOAD}) may give additional insight into the effects of different resistance training protocols.

The primary aim of the study was to investigate and compare the responses of END athletes to STR athletes when performing either a MS or MP block in conjunction with their sport specific training.

7.3 Methods

Experimental Design

To determine the effects of either a MS or MP resistance training program on neuromuscular responses in sub-elite END vs STR athletes during specific 4-week training blocks.

Subjects

Ten athletes from an elite sports institute were recruited to participate in the study. Athletes were split in to two groups depending on the predominant physiological characteristic trained, i.e. rowing athletes were placed in the END group (3 males and 2 females), while sprint cyclists were placed in the STR group (2 males and 3 females). Subject characteristics are shown in Table 7.1.

Table 7.1. Athlete characteristics for the Endurance and Strength/Power groups (Mean ± SD)

	Endurance	Sprint
Age (y)	20.1 ± 0.7	22.2 ± 4.6
Height (m)	1.87 ± 0.04	1.70 ±0.07
Body mass (kg)	84.7 ± 7.2	73.6 ± 14.9
1RM Back squat (kg)	121.0 ± 31.1	111.0 ± 41.0

The subjects trained > 25 h/wk for their chosen sport including both sport specific and athletic preparation training, and had represented their chosen sport at U23 national championships or higher. Whilst they performed different sport-specific training, both groups of athletes were in their respective preparation periods, characterised by higher training loads. As such, it could be reasonably assumed that both groups (STR and END) were in similar phases of their annual training cycle. All athletes had extensive resistance training and sport specific experience. Rowing and cycling athletes were chosen due to their similarity in primary musculature involved in their sport, i.e. lower body. All subjects received a clear explanation of the study, including risks and benefits of participation and provided written consent before the start of the study. The study was approved by the James Cook University Human Ethics Committee.

Procedures

Prior to the beginning of the training study 1RM back squat was determined for each athlete. Successful completion of a repetition required the subject to squat until their thighs were parallel with the floor. Squat depth was monitored visually by the same experienced tester for all trials to ensure uniformity between subjects. 1RM was determined after specific warm-up sets were performed at 50% (five to eight repetitions), 70% (five repetitions) and 90% (one to three repetitions) of their previous 1RM score. A five minute rest period was allowed between efforts of 90% and above (Winchester et al., 2005).

Training study

The training study was conducted over 2 x 4-week blocks with athletes performing a 4-week MS block followed by a 4-week MP block during a preparation period macrocycle. At the beginning of the first training session each week, athletes performed a standardised dynamic warm-up concluding with a set of five CMJ of increasing intensity, culminating with a maximal effort jump. Following a minimum 3 minute rest, subjects then performed 3 maximal CMJ_{BW} and CMJ_{LOAD}. A rest of 60 s was given between trials for both types of jumps and a minimum of 3 minute rest between CMJ_{BW} and CMJ_{LOAD} test sets. The load used for the CMJ_{LOAD} was 30% of the subjects back squat 1RM and was rounded to the nearest kilogram as used in previous research (Haines & Deakin, 2014) and was kept consistent for the duration of the study. This load was selected as it was a familiar training load used by all athletes and was therefore deemed not to place the athletes at undue risk. To avoid change due to diurnal variation, testing was performed at the same time of day for each athlete, although due to logistical reasons the testing time was different between groups (END = 15:30-17:00; STR = 09:30-11:00). All jumps were performed on a, portable force plate (AMTI, Frappier Acceleration, USA) with a sampling frequency of 200Hz. Countermovement depth was self-selected with the subject instructed to utilise a technique that would result in the maximum height possible. To maintain a similar jumping technique and allow for comparison between the two types of jumps, a wooden broom stick (mass = 0.7 kg) was used for each CMJ_{BW} to simulate the bar used in the CMJ_{LOAD}. Data was collected using DartPower software version 1.6 and analysed using custom-designed software using the impulse momentum approach as described by Andersson et al. (Andersson et al., 2008). A fourth-order, low-pass Butterworth digital filter with a cut-off frequency of 10 Hz was used to filter and smooth the data. The only cue given to the athlete was to maximize jump height, as such the jump that elicited the highest jump height was selected for analysis. Each CMJ_{BW} and CMJ_{LOAD} was analysed for a number of performance and technique related variables (Gathercole et al., 2015a; Gathercole et al., 2015b). The variables targeted for further analyses included three performance related variables; jump height from force (CV = 3.4%), relative peak power (CV = 3.4%), relative peak force (CV = 5.1%) and two technique related variables; centre of gravity (CG) downwards movement (CV = 7.2%), concentric: eccentric ratio (CV = 7.6%). Each variable was considered as reliable due to their CV being less than 10% (Haines et al., 2016).

During the 4-week training blocks subjects performed a program focussed on developing either MS or MP. Programs varied slightly between athletes due to exercise selection, although intensity and volume remained similar between athletes and groups. This method was chosen because it reflects program design and implementation within an applied setting. Whilst it introduced some variability due to exercise selection, this was not biased towards either the END or STR group. The same, experienced strength coach oversaw the programming, training and testing of all athletes to ensure consistency.

Statistical Analyses

Weekly data is expressed as means ± SD. Individual changes in jump performance were log transformed and plotted. For each variable, we calculated within-condition changes during the 4-week training block using within subject modelling (Hopkins, 2010). For example, individual slope was calculated and then used to determine a predicted change across the 4 weeks for each training group, END and STR during both periods, MS and P. Difference in the changes in means for END vs STR were then calculated using a modified statistical spreadsheet (Hopkins, 2006a). Thresholds for harmful or beneficial change were determined as a factor of CV. The CV for jump height was 3.4%, for relative peak power 3.4%, relative peak force 5.1%, centre of gravity downwards movement 7.2% and concentric: eccentric ratio 7.6% as found previously (Haines et al., 2016). Chances the differences were a 'true' effect were evaluated qualitatively as follows: 25-75% possibly, 75-95% likely, 95-99% very likely and > 99% almost certainly. If the 90% CI overlapped both threshold boundaries the change was deemed unclear and any true change falling within the boundaries deemed trivial. The magnitude of change was expressed as ES and was calculated using 0.2 x between-athletes SD with the following threshold inferences used: ≤0.2 (trivial), >0.2 (small), >0.6 (moderate), >1.2 (large), >2.0 (very large) and >4.0 (extremely large) (Hopkins et al., 2009).

7.4 Results

Weekly data for selected jump variables (CMJ_{BW} and CMJ_{LOAD}) for both the END and STR groups are presented for both the MS (Table 7.2) and MP blocks (Table 7.3).

Difference in changes in means during the MS block for the END vs STR group in the CMJ_{BW} variables are shown in Figure 7.1. The difference in mean (mean ± 90% CL) for relative peak power was likely higher for the STR group compared with the END group (7.8% ± 4.8%, chances that the true difference were higher/trivial/lower, 94/6/0 %). Within the CMJ_{LOAD} (Figure 7.2), relative peak power was possibly higher comparing the STR with END group (5.9% ± 8.3%, 71/26/3 %) whilst jump height was likely higher (8.4% ± 8.5%, 86/13/1 %). However, in contrast to the MS block, the change in concentric: eccentric ratio for the STR group was likely higher than that observed for the END group (14.8% ± 10.3%, 90/10/0 %).

During the MP block relative peak power showed similar results in the CMJ_{BW} (Figure 7.3) to those seen during the MS block with the STR group again displaying a likely higher change in mean when compared with the END group (9.8% ± 8.6%, 91/8/1 %). However, unlike the MS block, jump height also showed a likely higher change in mean between the STR and END groups (8.0% ± 6.4%, 90/10/0 %). The CMJ_{LOAD} showed likely higher changes for the STR vs END group (Figure 7.4) in both relative peak power (7.0% ± 5.7%, 87/13/0 %) and jump height (5.2% ± 4.6%, 77/23/0 %). Like the MS block concentric: eccentric ratio also showed a clear difference however the direction of the difference was reversed with the STR group displaying a likely lower change (-14.1% ± 7.7%, 0/7/93 %).

Table 7.2. Mean ± SD of variables for both the bodyweight countermovement jump and loaded countermovement jump during a 4-week maximum strength training block

		Bodyweight CMJ				Loaded CMJ			
	Group	Week 1	Week 2	Week 3	Week 4	Week 1	Week 2	Week 3	Week 4
Jump height (m)	Endurance	0.40 ± 0.08	0.410 ± 0.08	0.41 ± 0.08	0.39 ± 0.06	0.26 ± 0.04	0.27 ± 0.04	0.27 ± 0.04	0.25 ± 0.03
	Strength	0.43 ± 0.05	0.43 ± 0.05	0.42 ± 0.05	0.44 ± 0.04	0.27 ± 0.03	0.27 ± 0.03	0.27 ± 0.03	0.27 ± 0.03
Relative peak power ($W.kg^{-1}$)	Endurance	50.9 ± 8.4	51.2 ± 7.8	50.5 ± 7.9	48.8 ± 6.5	50.0 ± 8.5	51.0 ± 7.7	51.2 ± 7.3	48.8 ± 7.0
	Strength	57.1 ± 4.7	56.6 ± 4.9	57.7 ± 6.0	57.9 ± 4.4	56.2 ± 6.9	57.9 ± 5.9	57.5 ± 6.2	57.7 ± 5.0
Relative peak force (BW)	Endurance	2.25 ± 0.25	2.25 ± 0.22	2.27 ± 0.25	2.21 ± 0.22	2.80 ± 0.17	2.85 ± 0.18	2.82 ± 0.19	2.81 ± 0.18
	Strength	2.38 ± 0.22	2.36 ± 0.17	2.37 ± 0.10	2.35 ± 0.06	2.49 ± 0.21	2.52 ± 0.20	2.53 ± 0.17	2.49 ± 0.21
Centre of gravity movement (m)	Endurance	0.43 ± 0.06	0.45 ± 0.05	0.45 ± 0.03	0.45 ± 0.05	0.45 ± 0.04	0.45 ± 0.04	0.44 ± 0.06	0.43 ± 0.08
	Strength	0.38 ± 0.06	0.42 ± 0.05	0.39 ± 0.07	0.40 ± 0.07	0.38 ± 0.06	0.38 ± 0.07	0.39 ± 0.06	0.39 ± 0.05
Concentric: eccentric ratio (%)	Endurance	46.3 ± 8.4	51.4 ± 3.4	49.3 ± 4.8	50.9 ± 4.9	59.4 ± 7.5	57.9 ± 2.7	57.8 ± 8.2	56.4 ± 5.2
	Strength	51.5 ± 1.2	52.7 ± 5.2	52.3 ± 3.5	54.8 ± 1.3	57.7 ± 4.8	55.1 ± 3.8	59.4 ± 7.1	58.3 ± 3.8

*BW: Bodyweight

Table 7.3. Mean ± SD of variables for both the bodyweight countermovement jump and loaded countermovement jump during the a 4-week maximum power training block

		Bodyweight CMJ				Loaded CMJ			
	Group	Week 1	Week 2	Week 3	Week 4	Week 1	Week 2	Week 3	Week 4
Jump height (m)	Endurance	0.40 ± 0.08	0.41 ± 0.09	0.41 ± 0.09	0.41 ± 0.09	0.25 ± 0.03	0.26 ± 0.04	0.25 ± 0.04	0.25 ± 0.03
	Strength	0.41 ± 0.04	0.44 ± 0.06	0.44 ± 0.05	0.44 ± 0.06	0.26 ± 0.04	0.27 ± 0.03	0.28 ± 0.04	0.27 ± 0.03
Relative peak power ($W.kg^{-1}$)	Endurance	50.5 ± 7.7	50.2 ± 8.0	49.9 ± 8.4	49.5 ± 8.5	50.2 ± 6.3	50.7 ± 6.9	50.0 ± 6.4	49.6 ± 6.6
	Strength	56.2 ± 6.1	57.3 ± 6.1	58.6 ± 6.1	57.6 ± 5.1	55.5 ± 5.6	57.0 ± 6.8	57.8 ± 6.6	57.5 ± 6.3
Relative peak force (BW)	Endurance	2.11 ± 0.13	2.19 ± 0.25	2.20 ± 0.16	2.24 ± 0.21	2.79 ± 0.13	2.80 ± 0.18	2.82 ± 0.16	2.83 ± 0.19
	Strength	2.35 ± 0.13	2.35 ± 0.23	2.39 ± 0.14	2.43 ± 0.27	2.53 ± 0.15	2.54 ± 0.16	2.62 ± 0.19	2.64 ± 0.24
Centre of gravity movement (m)	Endurance	0.46 ± 0.04	0.48 ± 0.04	0.49 ± 0.03	0.50 ± 0.03	0.49 ± 0.06	0.51 ± 0.05	0.52 ± 0.65	0.53 ± 0.05
	Strength	0.38 ± 0.06	0.40 ± 0.06	0.40 ± 0.08	0.40 ± 0.07	0.40 ± 0.07	0.39 ± 0.07	0.40 ± 0.08	0.39 ± 0.08
Concentric: eccentric ratio (%)	Endurance	53.0 ± 6.6	53.4 ± 6.0	50.4 ± 9.3	56.0 ± 5.7	62.6 ± 6.7	64.9 ± 7.7	64.8 ± 8.2	67.7 ± 5.9
	Strength	54.2 ± 4.4	54.1 ± 3.6	54.4 ± 5.6	55.6 ± 3.0	62.1 ± 4.6	60.9 ± 5.7	57.0 ± 2.4	60.5 ± 4.7

*BW: Bodyweight

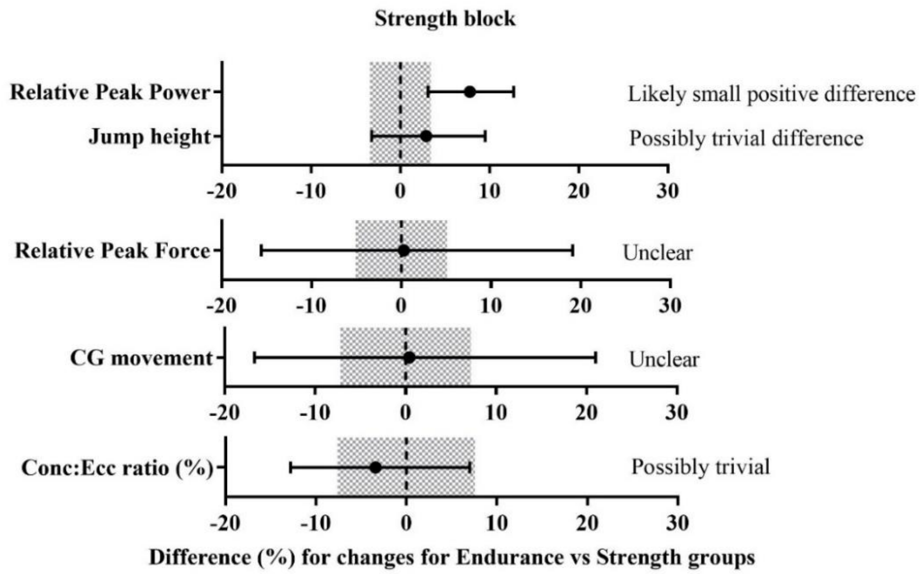

Figure 7.1. Endurance vs Strength/Power group bodyweight countermovement jump mean changes in response to a maximum strength training block. Descriptive terms for each variable indicate the likelihood an effect is a true effect, the magnitude of the effect and the direction of the effect. The shaded area indicates the trivial effect boundaries for each specific variable expressed as a percentage.

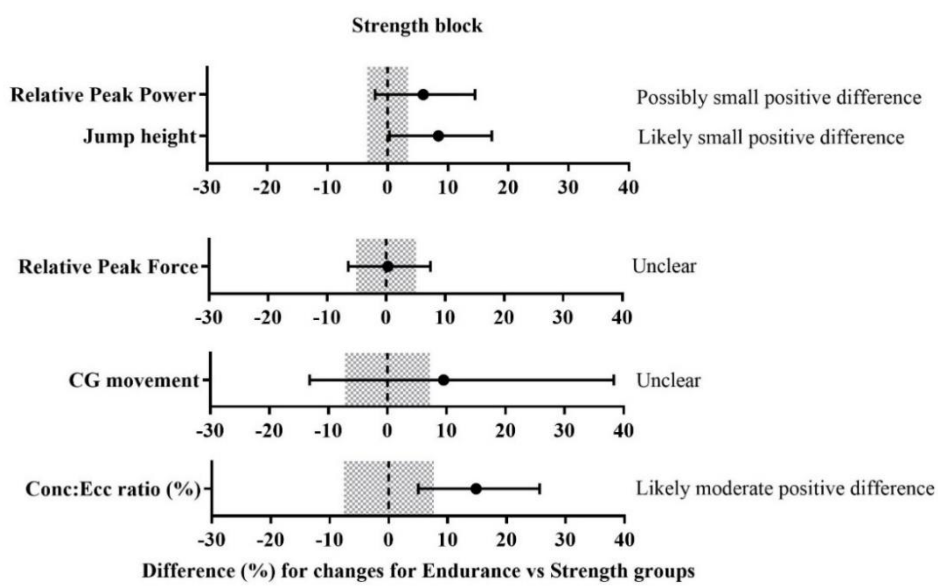

Figure 7.2. Endurance vs Strength/Power group loaded countermovement jump mean changes in response to a maximum strength training block. The shaded area indicates the trivial effect boundaries for each specific variable expressed as a percentage.

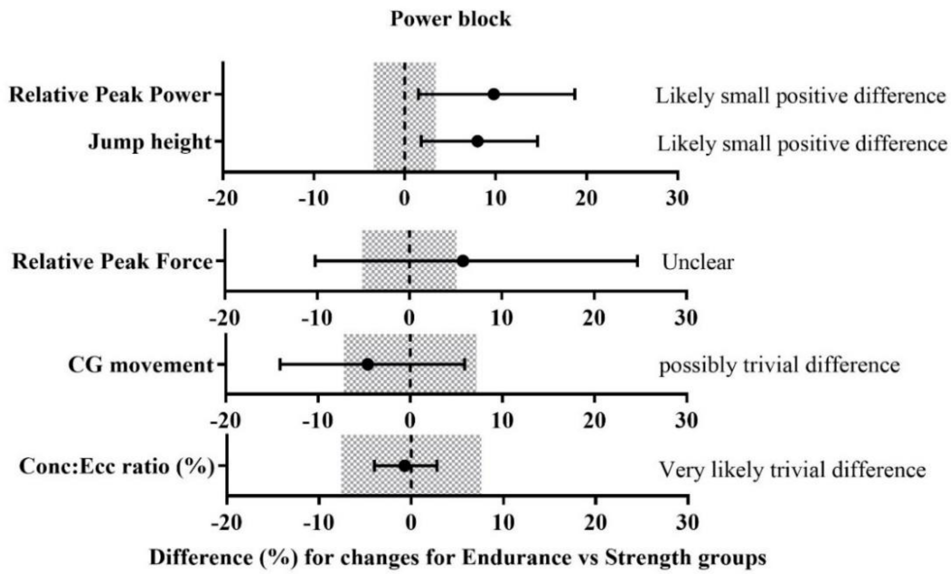

Figure 7.3. Endurance vs Strength/Power group bodyweight countermovement jump mean changes in response to a maximum power training block. The shaded area indicates the trivial effect boundaries for each specific variable expressed as a percentage.

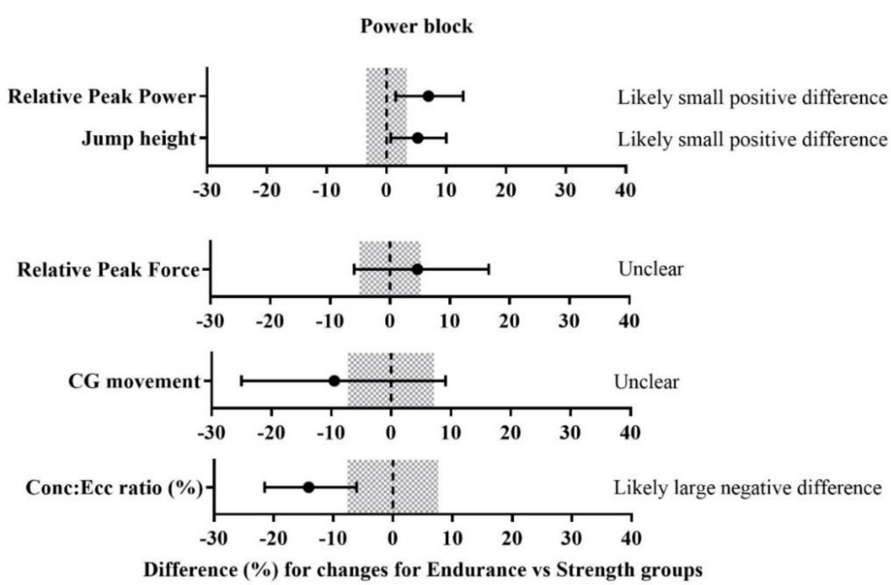

Figure 7.4. Endurance vs Strength/Power group loaded countermovement jump mean changes in response to a maximum power training block. The shaded area indicates the trivial effect boundaries for each specific variable expressed as a percentage.

7.5 Discussion

The present study investigated how END versus STR athletes responded to common resistance training blocks used in athletic development performed concurrently with their typical sport-specific training. The primary finding was that STR based athletes show better performance gains compared with END athletes when comparing changes in CMJ_{BW} and CMJ_{LOAD} during 4-week MS and MP training blocks.

During the STR block the only CMJ_{BW} performance related variable to demonstrate a clear difference between the two training groups was relative peak power which improved more for the MS group than the END group (Figure 7.1). No clear differences were observed in any of the technique related variables suggesting that this change was due to alterations in neuromuscular function and not the technique chosen. Over the same training period CMJ_{LOAD} performance showed clear differences between two variables with both relative peak power and jump height improving to a greater extent for the MS group when compared with the END group (Figure 7.2). However, a clear difference in the change in technique used to perform the jump was observed between the two training groups over the training block (Figure 7.2) with concentric: eccentric ratio increasing more for the MS group than END group. Such an increase in ratio suggests a faster eccentric phase in relation to the concentric phase indicating a more 'dynamic' countermovement was chosen. This difference in technique was further reflected by differences in some performance variables. The more dynamic countermovement could indicate an increased ability to produce the force required to perform an efficient countermovement resulting in the improved performance variables of jump height and relative peak power. The absence of associated changes in relative peak force suggest that rather than a change in the magnitude of the force produced, possible changes in the RFD may explain these differences in performance as previous research has shown this to be highly correlated with CMJ performance (McLellan, Lovell, & Gass, 2011). Previous research examining various CMJ protocols either using bodyweight only or additional load has found that using a heavier external load increases the magnitude of change seen in peak force across a 12-week period (Sheppard et al., 2008a). It should be noted however that the use of peak force instead of relative peak force may result in different findings.

During the MP block, the changes in both relative peak power and jump height showed clear differences between both training groups. The MS group demonstrated a likely larger change in the aforementioned variables compared with the change seen in the END group (Figure 7.3). As with the STR block, this appeared due to neuromuscular changes as no clear difference existed between the groups in relation to the technique related variables (Figure 7.3).

In comparison to the CMJ_{BW} the CMJ_{LOAD} showed similar effects, with the changes in relative peak power and jump height showing clear differences between both training groups with the MS group again showing likely higher changes when compared with the END group (Figure 7.4). These performance based changes were also reflected in technique related changes, with the changes in concentric: eccentric ratio showing a clear difference between groups (Figure 7.4). Interestingly, this effect was the opposite to the effect on CMJ_{LOAD} seen during the STR block with the MS group showing a likely decrease in the change of the ratio over the training block when compared with the change observed in the END group during the same period (Figure 7.2).

The results from the current study show that when comparing changes in performance during a resistance training block (MS or MP) between STR and END athletes, the CMJ_{BW} is a good choice of test. These results support the findings of Gathercole et al. (2015a). This is due to the lack of difference observed in technique based variables, indicating that any changes in performance can be attributed to neuromuscular changes (Figures 7.1 & 7.3). Conversely, CMJ_{LOAD} may not be as appropriate for assessing changes in athletic performance due to the coinciding change in technique as observed via the changes in concentric: eccentric ratio (Figures 7.2 & 7.4). However, despite an apparent trend for changes in centre of gravity (CG) movement to track in the same direction as concentric: eccentric ratio, no clear differences were seen in CG movement between the MS and END group during either the MS (Figure 7.2) or MP (Figure 7.4) training block. With this in mind, the authors contend that based on available data, the change in this ratio is more related to improved force/velocity characteristics as opposed to any change in the depth of countermovement chosen.

The larger changes observed in general for the STR group vs END athletes may be explained by an increased ability to produce greater muscle activation during resistance training as observed previously (Ahtiainen & Häkkinen, 2009; Tillin, Jimenez-Reyes, Pain, & Folland, 2010). Whilst this previous study compared strength athletes with non-athletes, it may be the case that similar differences are likely between strength/power and endurance athletes (Ahtiainen & Häkkinen, 2009). Caution must be shown in interpreting the results from this study as the subject number was low for both groups (n = 5) due to the elite nature of athletes included in the study. To account for this small sample size, analyses and interpretation has been based around the magnitude of change as used in similar research (Gathercole et al., 2015b).

7.6 Conclusion and practical applications

Due to the widespread use of resistance training to develop physical performance, it is fundamental to understand the difference in performance athletes from various sport types may expect from completing similar resistance training programs. This novel study showed that similar resistance training performed whilst undertaking different sport-specific training did not result in similar strength or power gains. Specifically, STR based athletes can expect consistently higher changes during both MS and MP training blocks when compared with END athletes. This is regardless of the training block assessed (MS vs MP) or the assessment tool used (CMJ_{BW} vs CMJ_{LOAD}). Such differences must be considered by the strength and conditioning staff when planning a training program. If such performance markers are important for overall success in their chosen sport sufficient time must be allocated to develop these qualities given the likely differing time frames required depending on the nature of concurrent, sport-specific training being performed.

A four-week resistance training block of either maximum strength or maximum power training performed concurrently with sport-specific training shows clear effect differences between STR (sprint cyclists) and END athletes (rowers).

Chapter 8

Monitoring in-season neuromuscular performance in Australian rules football players using different types of countermovement jump

Haines, B., Poulos, N., Bourdon, P., & Deakin, G. (Submitted). Monitoring in-season neuromuscular performance in Australian rules football players using different types of CMJ. *Journal of Sports Science & Medicine*.

This study was designed as a follow up to Chapter 6, after determining the effectiveness of the CMJ_{BW} and CMJ_{LOAD} in assessing neuromuscular readiness over a longitudinal preparation period in an individual athlete. Subsequently, the authors wanted to replicate this assessment method within the in-season period of an elite team sport and monitor the impact of weekly training and competition. This study addresses the challenges of assessing elite team sport athletes competing in a weekly competition.

8.1 Abstract

Purpose: To compare the pattern and magnitude of neuromuscular fatigue measured via a bodyweight countermovement jump (CMJ_{BW}) and loaded countermovement jump (CMJ_{LOAD}) in elite Australian rules football (AFL) players. **Methods:** Six male AFL players performed 3 maximal CMJ_{BW} and CMJ_{LOAD} weekly over a 5-week in-season period which were compared to baseline measurements. Meaningful changes (ES ± 90% CL) in neuromuscular readiness were assessed using a magnitude-based inferences approach along with qualitative descriptors of change. Of specific interest were jump height, peak power, relative peak power and centre of gravity movement and these were analysed for both jump types. **Results:** Both the CMJ_{BW} and CMJ_{LOAD} were sensitive to performance and technique based changes at various time points. CMJ_{BW} was the most sensitive to changes in jump height (week 2, -0.79 ± 0.38; week 4 -0.85 ± 0.48 and week 5, -0.36 ± 0.50) whilst CMJ_{LOAD} was the most sensitive to changes in both centre of gravity movement (week 2, -0.50 ± 0.44 and week 5, -0.43 ± 0.32) and relative peak power (week 2, -0.55 ± 0.42; week 3 -0.31 ± 0.60; week

4, -0.66 ± 0.79 and week 5, -0.57 ± 0.77) showing clear fatigue effects at various time points that matched with predicted fatigue. **Conclusions:** Both CMJ_{BW} or CMJ_{LOAD} may be used to assess neuromuscular readiness in elite AFL players. Practitioners should use a combination of technique and performance related variables to maximise the accuracy of any decisions based on the data.

8.2 Introduction

Monitoring acute neuromuscular fatigue in athletes has become common place in elite sport with practitioners choosing from a variety of tests and their associated variables to determine neuromuscular readiness (Cormack et al., 2008a; Cormack et al., 2008c; Gathercole et al., 2015b; Haines & Deakin, 2014). Different types of neuromuscular performance tests, such as the CMJ and DJ have displayed similar fatigue time courses whilst other tests such as the 20-m sprint may display different time courses (Gathercole et al., 2015a). These time course variations in fatigue highlight the need for an appropriate test(s) to monitor the fatigue versus freshness state of athletes and help inform practitioners as to their readiness to compete.

This is especially important in weekly competition, team-sports such as Australian Rules Football (AFL). Previous research has shown that the CMJ is very useful for neuromuscular monitoring due to its high repeatability compared to other tests such as the DJ (Gathercole et al., 2015a). Additionally, the CMJ has also been shown to detect neuromuscular fatigue for longer after fatiguing, running based events compared to other highly repeatable tests such as the 20-m sprint (Gathercole et al., 2015a). Specific AFL research has established the CMJ's usefulness as a diagnostic tool to assess neuromuscular fatigue in elite AFL players 24 h post-match (Cormack et al., 2008c). In determining the appropriate time to conduct fatigue monitoring assessments Cormack et al examined neuromuscular fatigue throughout an AFL season and found that players showed neuromuscular fatigue up to 144 h post-match (Cormack et al., 2008a).

The use of a single test, such as the CMJ may not give a clear indication of all the fatigue experienced by players during an AFL season or of any differences in their fatigue-recovery time course. Given the effectiveness of the body weight CMJ (CMJ_{BW}) as a monitoring tool (Cormack et al., 2008a) it may be that the use of a loaded CMJ (CMJ_{LOAD}) may give additional precision in detecting the impacts of fatigue generated from AFL preparation and competition and any variations in their time course. In assessing muscle force and power capacities, recent research has advocated the use of the 'Two-Load Method' which strengthens the argument for the inclusion of the CMJ_{LOAD} as a potential tool for monitoring fatigue (Jaric, 2016; Pérez-Castilla, Jaric, Feriche, Padial, & García-Ramos, 2017). Previous research has shown that peak power relative to body mass measured via a CMJ_{LOAD} is significantly different at 27% of back squat 1-repetion maximum (1RM) compared with a CMJ_{BW}

(Cormie et al., 2007b). Therefore, 30% 1RM may be an acceptable external load to detect different neuromuscular fatigue responses in elite AFL athletes.

The aim of this study was therefore to investigate whether CMJ_{BW} and CMJ_{LOAD} at 30% of back squat 1RM have different neuromuscular fatigue responses and time courses in elite AFL players during an in-season monitoring period.

8.3 Methods

Experimental Approach to the Problem

To monitor the effects of an in-season strength /power block on power characteristics, players performed weekly neuromuscular testing over a five-week period (Rounds 7-11). This specific period and protocol was chosen for several reasons. Firstly, it was hypothesised that after six rounds players would be well adapted to the physical demands of the competition thus allowing for a stable physiological response after each match. Secondly, Round 7 corresponded with the beginning of a new strength training cycle and allowed for a similar training exposure across the collection period. Thirdly, it allowed the use of a current in-season baseline instead of one determined pre-season to compare the changes in physiological demands of a typical in-season week.

Subjects

Forty-six male AFL players training with a club in the national competition participated in the study. All players were contracted by the club, trained as a group and played in either the national or development league teams. Only data from players who played in the national league team for each of the five weeks monitored were included in the analyses. Subject consent was given by the club as a part of the athlete's training agreement. Players also gave their consent and the study was approved by the James Cook University Human Ethics Committee.

Procedures

During test sessions players performed a minimum of three CMJ_{BW} and three CMJ_{LOAD} at 30% of their estimated Back Squat 1RM. To ensure similarity between jump types a wooden dowel was held across the shoulders for each CMJ_{BW} trial whilst a barbell loaded to a total mass equal to 30% of the subject's Back Squat 1RM was used for each CMJ_{LOAD}. If any trial was not completed correctly a replacement trial was performed. All data was collected using the Ballistic Measurement System and software (BMS; Fit-ness Technology, Adelaide, Australia) incorporating a force plate (400 series;

Fitness Technology, Adelaide, Australia) sampling at 600 Hz. Testing was performed at either 9:30 am or 12:30 pm on the 2nd day post-match. The testing days and times were immediately prior to the first main training session after the preceding game and as such were dictated by the clubs training schedule and outside the control of the researchers. Due to the varied nature of elite AFL, several variables that may impact on neuromuscular readiness such as home/away match (i.e. impact of travel and testing time (circadian rhythm) could not be fully controlled and therefore could be considered a limitation of the study. These variables are presented in Table 8.1 to allow the reader to observe any impact these data may have on neuromuscular readiness. Match workload data was unable to be used in the comparisons due to the missing workload data (GPS derived) for those games played indoors.

Each trial was analysed using custom designed software (Force Test Analyser - Aspire) incorporating a Butterworth Low-Pass 4th order filter with a cut-off frequency of 10 Hz. The best trial selected based the highest jump height as determined by force was used in subsequent analyses.

Table 8.1. Time of testing, match location and results for the in-season period assessed

Week (Round)	Testing time	Home / Away	Win / Loss
1 (7)	12:30 pm	Home	Win
2 (8)	9:30 am	Away	Win
3 (9)	12:30 pm	Home	Loss
4 (10)	9:30 am	Away	Win
5 (11)	9:30 am	Bye	Bye

Statistical Analyses

Weekly data are expressed as means ± SD. Differences in the change in means were calculated using a modified statistical spreadsheet (Hopkins, 2006a). The magnitude of change from baseline (week 1 testing) compared with subsequent weeks was expressed as ES and 90% CL and was calculated using 0.2 x between-athletes SD with the following threshold inferences used: ≤0.2 (trivial), >0.2 (small), >0.6 (moderate), >1.2 (large), >2.0 (very large) and >4.0 (extremely large). If both 90% CL overlapped both small ES boundaries, the changes were deemed unclear (Hopkins et al., 2009). A qualitative description of the chance the change/difference was a true effect was evaluated as follows: 25-75% possibly; 75-85%, likely; 95-99%, very likely; >99%, almost certainly (Hopkins et al., 2009).

8.4 Results

Due to differing player availability during the testing period, only six athletes completed all five consecutive weekly test sessions. The weekly data for selected jump variables for these athletes are presented in Table 8.2 (CMJ_{BW}) and Table 8.3 (CMJ_{LOAD}).

When considering both types of jump the following trends were observed. CMJ_{BW} jump height appeared to be the most sensitive to change during this period showing clear, possible small to very likely moderate effects at 3 different time points; week 2 (ES = -0.79 ± 0.38, 99%), week 4 (-0.85 ± 0.48, 98%) and week 5 (-0.36 ± 0.50, 72%) (Figure 8.1). CG movement showed a clear, possible small effect at week 2 (-0.23 ± 0.40, 58%). In observing the results from the CMJ_{LOAD}, relative peak power was the most sensitive to change with clear, likely small or moderate effects observed at weeks 2 (-0.55 ± 0.42, 92%), 4 (-0.66 ± 0.79, 85%) and 5 (-057. ± 0.77, 83%) (Figure 8.2). CMJ_{LOAD} peak power and jump height were also seen to be sensitive performance measures of change. CG movement appeared to be a sensitive technical measure of change with both weeks 2 (-0.50 ± 0.44, 88%) and 4 (-0.43 ± 0.32, 90%) showing likely small effects.

Table 8.2. Weekly mean ± SD scores for the bodyweight countermovement jump variables

Variable	Week 1	Week 2	Week 3	Week 4	Week 5
Jump height (m)	0.39 ± 0.03	0.36 ± 0.03	0.39 ± 0.03	0.36 ± 0.03	0.38 ± 0.04
Peak power (W)	4579 ± 624	4416 ± 653	4615 ± 623	4460 ± 603	4554 ± 689
Relative peak power ($W.kg^{-1}$)	51.8 ± 4.9	50 ± 4.8	52.3 ± 4.5	50.4 ± 4.4	51.3 ± 5.5
Centre of gravity movement (m)	0.34 ± 0.04	0.33 ± 0.04	0.34 ± 0.06	0.32 ± 0.05	0.33 ± 0.05

Table 8.3. Weekly mean ± SD scores for the loaded countermovement jump variables

Variable	Week 1	Week 2	Week 3	Week 4	Week 5
Jump height (m)	0.27 ± 0.03	0.24 ± 0.02	0.25 ± 0.02	0.24 ± 0.02	0.25 ± 0.02
Peak power (W)	4713 ± 511	4428 ± 490	4568 ± 533	4382 ± 516	4454 ± 648
Relative peak power ($W.kg^{-1}$)	53.5 ± 5.2	50.1 ± 2.9	51.5 ± 3.5	49.6 ± 4.2	50.1 ± 5.4
Centre of gravity movement (m)	0.33 ± 0.06	0.30 ± 0.07	0.32 ± 0.07	0.32 ± 0.07	0.30 ± 0.06

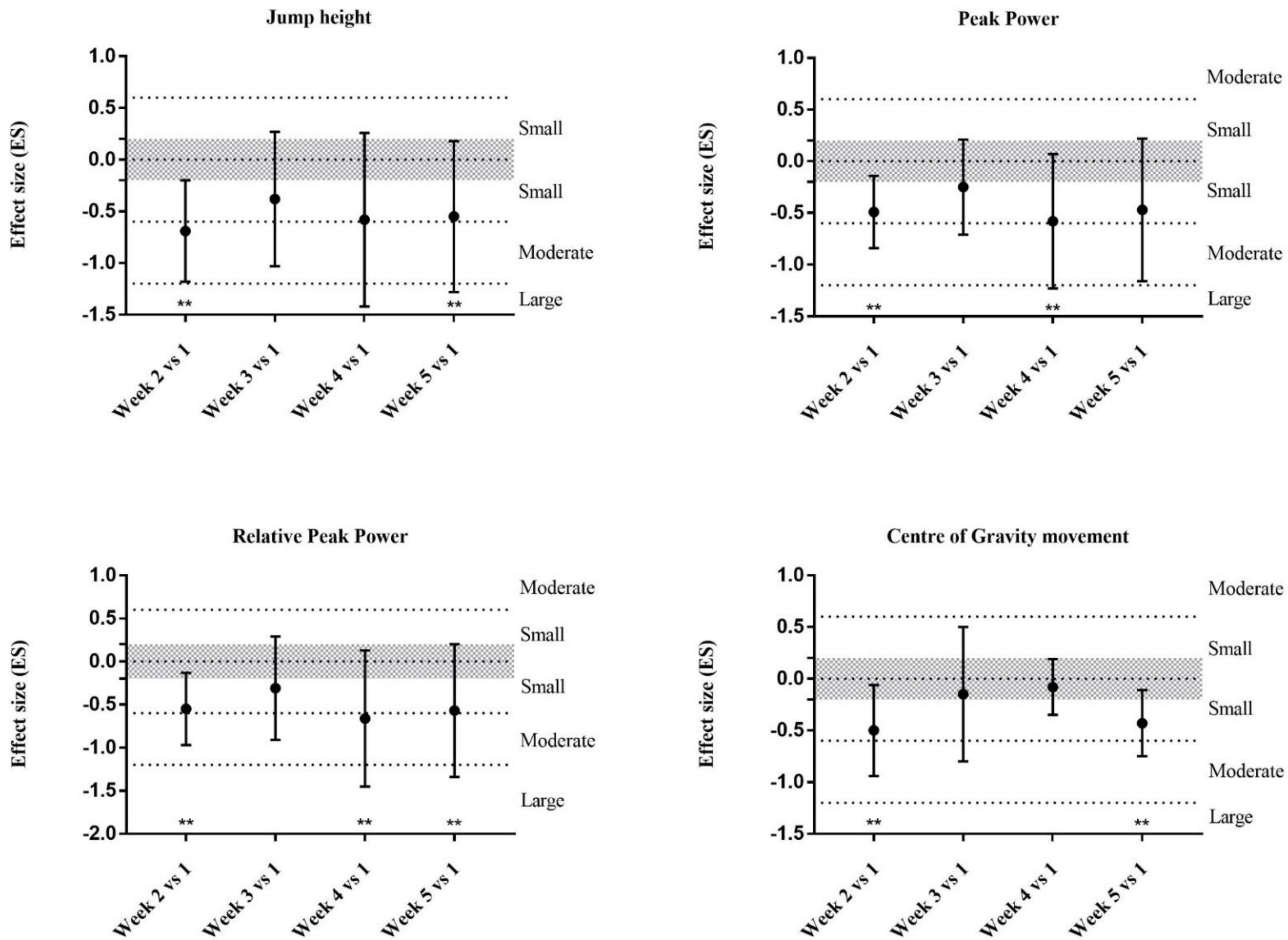

Figure 8.1. The neuromuscular readiness of AFL players as assessed by bodyweight countermovement jump variables across a 5-week period. The number of asterisks (*) indicate the likelihood for the between-groups differences to be substantial; * = possible, ** = likely and *** = very likely

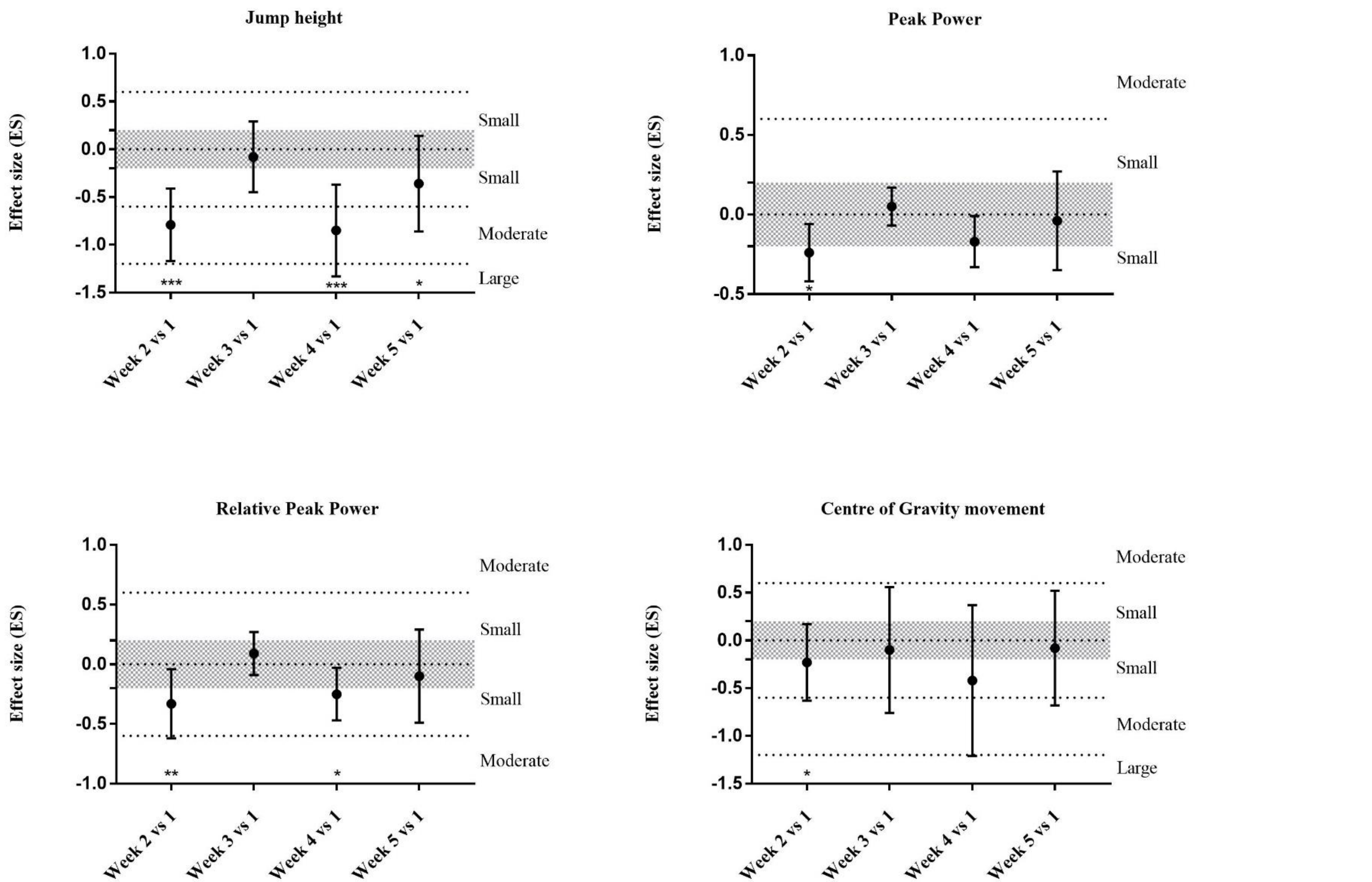

Figure 8.2. The neuromuscular readiness of AFL players as assessed by loaded countermovement jump variables across a 5-week period. The number of asterisks (*) indicate the likelihood for the between-groups differences to be substantial; * = possible, ** = likely and *** = very likely

8.5 Discussion

This study provides novel and practical findings regarding the use of either CMJ_{BW} or CMJ_{LOAD} to monitor acute neuromuscular function and readiness in elite AFL players. CMJ_{BW} appears to be more sensitive to changes in jump height whilst CMJ_{LOAD} may be more sensitive to changes in relative peak power and centre of gravity movement.

In the current study, the players performed a typical in-season schedule consisting of a weekly game (except for week 5 - bye) and concurrent training program including sport specific and athletic preparation. In examining the results of the neuromuscular assessments during this period, the acute response pattern of CG movement shown in the CMJ_{BW} indicate that the players jump strategy were very consistent across the testing period with only a small, clear effect (-0.23 ± 0.40, 58%) seen in week 2 (Figure 8.1). This negative effective size indicates that a smaller countermovement or 'dip' preceded the jump which may indicate a decreased level of neuromuscular fatigue when compared with week 1 as has been proposed in previous research (Gathercole et al., 2015a). In considering the other CMJ_{BW} performance variables, clear moderate decreases in jump height (week 2 = -0.79 ± 0.38, 99%; week 4 = -0.85 ± 0.48, 98%) and clear small decreases in relative peak power (week 2 = -0.33 ± 0.29, 79%; week 4 = -0.25 ± 0.22, 67%) were also observed. Whilst it could be assumed that these results are reflective of a decreased level of neuromuscular preparedness, differences in testing times as presented in Table 8.1 (weeks 2 and 4 at 9.30 am; baseline/week 1 at 12.30 pm) may have had a negative impact on performance as previously reported by Taylor et al. (2010). However, it should be noted that the time difference in that study was 6 h (8am – 2pm) as opposed to 3 h in the current study. In addition, whilst Taylor et al. (2010) found that time of day resulted in relative peak power improving by approximately 5% from AM to PM, the increase seen in the present study was on average, less than 3%.

CMJ_{LOAD} results showed centre of gravity movement being moderately affected at weeks 2 (-0.5 ± 0.44, 88%) and 5 (-0.43 ± 0.32, 90%) with a smaller countermovement (dip) reported for both weeks compared to week 1. This is similar to the results seen for CMJ_{BW}, but of greater likelihood, confirming that time of day may impact the depth of countermovement selected in a CMJ. Other CMJ_{LOAD} performance variables also displayed similar results to CMJ_{BW} with jump height exhibiting a moderate decrease in week 2 (-0.69 ± 0.49, 95%) and small decrease in week 5 (-0.55 ± 0.73, 81%), while relative peak power showed a small decrease in weeks 2 (-0.55 ± 0.42, 92%) and 5 (-0.57 ± 0.77, 83%) and a moderate decrease in week 4 (-0.66 ± 0.79, 85%). Whilst these results indicate the presence of neuromuscular fatigue 48-h post an AFL match the design of the present study does not differentiate as to whether this fatigue is solely a result of the preceding match or is a combination of match and training factors. Interestingly, previous research in a similar population group detected fatigue as measured via a single CMJ performed

72-h post a single AFL match (Cormack et al., 2008c) and for at least 144-h post-match throughout a season (Cormack et al., 2008a), indicating that various assessment time points may be viable.

The fatigue patterns observed within both types of jump were similar across the 5 weeks with only week 3 showing no clear effects of fatigue for either the CMJ_{BW} or CMJ_{LOAD}. However, more data time points across a larger number of subjects would provide further addition to this area. To the authors knowledge, no previous research has used two different load CMJ's to assess fatigue in weekly team-sport athletes and as such these specifics from the current study cannot be compared. Without the corresponding match workload data, it is impossible to determine if the total workload the players were exposed to during this period were similar, which in turn may influence their level of preparedness for the subsequent monitoring. However, as observed in Table 8.1, the variables associated with week 3 were most like week 1, i.e. 12:30 pm testing time and a home game. This may indicate that time of testing may be of high importance in assessing neuromuscular fatigue during an AFL in-season as has been found in research for rugby union players (Taylor et al., 2010). Also, the reduced travel fatigue experienced during the home games (weeks 1 and 3) may account for their better performance scores and lower levels of fatigue (Tables 8.1 – 8.3) may effect performance as previous research has postulated (Leatherwood & Dragoo, 2012; Samuels, 2012) . Further research that utilises a longer testing period and higher subject numbers may provide greater insight into the neuromuscular response to weekly AFL matches assessed utilising two different load CMJ's. Caution must be shown in interpreting the results from this study as the subject number was low (n = 6) due to constraints of the research design.

8.6 Practical applications

To the authors' knowledge, this is the first study to investigate neuromuscular readiness via both CMJ_{BW} and CMJ_{LOAD}, in-season, on a weekly basis in AFL players. These data suggest that either jump type may be a useful diagnostic tool given the similar fatigue responses found. As has been noted elsewhere, technique and performance related variables should both been used when assessing neuromuscular fatigue in elite athletes (Gathercole et al., 2015a; Gathercole et al., 2015b). In addition, when selecting an assessment tool, practitioners should consider both the variables assessed within a test as well as the test itself. For example, jump height, relative peak power or centre of gravity movement may give an increased likelihood of detecting changes in fatigue when paired with the appropriate test (CMJ_{BW} or CMJ_{LOAD}).

8.7 Conclusion

This study demonstrates the ability of both the CMJ_{BW} and CMJ_{LOAD} to assess neuromuscular readiness in elite AFL players. Variables from both tests displayed levels of accuracy as strong as could be reasonably expected based on the variability of conditions encountered during a professional team during its competition season.

Chapter 9

Summary and Conclusion

9.1 Summary

The overall aim of this thesis was to examine the responses and adaptations of athletes to maximum strength and maximum power training during various preparation and in-season periods. As is typical with athlete preparation, these training blocks were performed in conjunction with period relevant, sport-specific training. The specific aims of the project were to (i) understand the neuromuscular and morphological adaptations to both a pre-season and in-season maximum strength resistance training protocol in elite adolescent athletes, (ii) determine the acute neuromuscular fatigue and recovery responses over a 48 h period after a maximum strength resistance training protocol at three different periods within the annual cycle in elite adolescent athletes, (iii) compare the weekly, lower body power adaptations of strength/power and endurance athletes to four-week maximum strength and maximum power training blocks, and (iv) examine the weekly neuromuscular responses of elite AFL players during a five-week in-season period.

A review of physiological adaptations to resistance training, specifically maximum strength and maximum power as utilised pre-dominantly by elite athletes, highlighted the various specific adaptations and responses that occur. Changes observed in morphological, neuromuscular and biochemical parameters are largely dictated by the specific program variables associated with the resistance training stimulus applied to an athlete (Tillin & Folland, 2014). Additionally, the use of common performance tests has been shown to be a time effective, practical and applied means of assessing the adaptations of athletes to a block of resistance training (Kyröläinen et al., 2005; Veliz et al., 2014) and to assess the acute effects and recovery dynamics of individual training sessions across a wide range of athletes (Brandon et al., 2015; Johnston, Cook, Crewther, Drake, & Kilduff, 2015).

To observe these adaptations and responses in adolescent athletes it was first important to determine the reliability of the assessment methods commonly used in adults to assess whether the same level of precision applied. Previous research has suggested that a CV of <10% is an acceptable level of reliability in adults and therefore, this same CV was applied to adolescent athletes (Cormack et al., 2008b). Whilst the use of a CV threshold such as this is useful in providing practical guidelines, it is an arbitrary guideline and S&C coaches should where possible, select tests and the associated variables with CV's as low as possible. Adolescent athletes displayed similar reliability of inter-day test results to adults across multiple performance and technical variables in the four neuromuscular tests used, CMJ (Moir et al., 2009; Sheppard et al., 2008a), DJ (Feldmann et al., 2011), IMTP (McGuigan & Winchester, 2008) and 20-m sprint (Fletcher & Jones, 2004) indicating that these tests may be used to monitor both chronic adaptations and acute response to resistance training in this population (Chapter 3).

These tests were then used to monitor an adolescent athlete cohort perform both an in-season and pre-season strength training block as a part of their overall training plan. The pre-season training period showed better improvements in back squat strength and specific neuromuscular tests such as CMJ. This was likely underpinned by morphological changes in lower body muscle mass such as the observed changes in VL thickness (Chapter 4) as has been previously observed (Cormie et al., 2010). The type of resistance training performed during a 'typical' pre-season maximum strength block appears not to have any effect on sprint-speed over 20-m and could possibly have a harmful effect on 5-m sprint time. The lack of change in 20-m sprint is likely due to the difference in contraction velocity observed between a low velocity maximum strength exercise and the high contraction velocity utilised in sprinting. Previous research has shown similar findings with maximum strength training resulting in no change in 30-m sprint time over a pre-season training period whilst a combination of strength and power training did (Harris, Stone, O'Bryant, Proulx, & Johnson, 2000). This premise was supported by the decrease in performance observed in the DJ across the same period, which also utilises a faster contraction velocity than observed in maximum strength training. In contrast, it has been reported that a program utilising a combination of low and high contraction velocity exercises such as the back squat and jumping activities respectively will likely have positive performance benefits on sprinting speed (Comfort, Haigh, & Matthews, 2012; Harris et al., 2000). It is unlikely that this is due to increases in maximum force production ability due to the lack of improvement in this physiological quality as measured via a back squat. However, improvements may be driven by changes in the athlete's ability to develop force quickly. Previous research substantiates this with Cronin & Hansen (2005) finding that whilst back squat 3RM did not correlate significantly with 5-m, 10-m and 20-m sprint time, faster contraction velocity tests such as CMJ height did. In general, the training adaptations that can be expected from a training period will be specific to the training stimulus as has been shown previously (Tillin & Folland, 2014).

For any training adaptations to occur, maximum strength training must be performed regularly and as such, will induce a specific neuromuscular fatigue response and recovery profile (Howatson et al., 2016). It is important to understand this fatigue and recovery profile as it may influence the scheduling of subsequent training sessions. For example, an athlete's ability to train with minimal fatigue may be an important consideration when the focus is developing physical, tactical or technical qualities. Maximum strength training exhibited a clear acute fatigue and recovery profile in adolescent athletes (Chapter 5) with the fatigue generated resulting in distinct recovery profiles across differing neuromuscular activities. For instance, activities involving peak force and long contraction times appear to be minimally affected by maximum strength, recovering within four hours of cessation of strength training. Previous research has found that peak force may still be negatively affected 24-h post a strength session however this study was performed on elite adult track and field athletes (Howatson et al., 2016) and utilised a different training regime.

In contrast, power activities that require shorter contraction times showed a slower recovery rate. This is indicated in the current study by CMJ performance variables such as jump height and peak force showing signs of fatigue up to 24 hours-post training, which is in support of the findings of Johnston et al. (2015). As the speed of the movement increases and thus decreases the time available for a forceful contraction, performance appears to become even more sensitive to fatigue generated from maximum strength training. Fast contraction speed exercises such as the DJ and 20-m sprint exhibited the negative performance effects of fatigue up to 48 hours later. Previous research examining CMJ, DJ and 20m sprint fatigue response has shown somewhat conflicting results (Gathercole et al., 2015a). The authors found that CMJ showed the largest fatigue effects 72-h post a fatiguing interval running session, whilst DJ and 20-m sprint showed similar but smaller effects. These differences may be a consequence of the different fatigue stimuli, i.e., strength training versus interval training.

Whilst this provides insightful information into the fatigue response of adolescent athletes after maximum strength training and the subsequent organisation of follow-up training sessions, Chapter 5 also highlighted the potential 'fatigue-resistance' benefits associated with the increases in strength observed following a maximum strength training block. The adolescent athletes were exposed to the same fatiguing strength stimulus at three separate occasions during their annual training cycle and showed that when athletes were at their strongest, as measured by their respective back squat 1RM, the fatiguing effects of the strength session appeared to be the smallest, despite the same relative intensity being used for the session. To the authors knowledge, no previous research has been conducted that would contribute to this premise.

It is at this point the neuromuscular readiness assessment tools initially used were changed for the rest of the thesis chapters. The initial four assessments used (CMJ, DJ, IMTP and 20-m sprint) were replaced by the CMJ_{BW} and CMJ_{LOAD}. This lack of continuity between assessment methods throughout the thesis may be viewed as a limitation. The change in assessment methods were a result of the author's change of employment and subsequent change in population group available for assessment. The athlete group available for Chapters 6-8 were elite athletes in either National teams or professional sports and as such were not available for multiple assessment methods in measuring neuromuscular readiness, as such, the simplified assessment method of the two-load approach was utilised (Jaric, 2016). This had the dual benefit of minimising the amount of time used for assessment and ensuring familiarity of the assessment tests for the athletes.

When monitoring neuromuscular fatigue/readiness in elite athletes, the use of a CMJ_{BW} or CMJ_{LOAD}, may both be acceptable tests (Chapter 6). Relative peak power was the variable that gave the best indication of the athlete's training status, with CMJ_{BW} being the most sensitive, detecting the restoration of performance during the tapering period whilst the CMJ_{LOAD} did not. This area requires further research as recent studies have supported the idea of two different loads being used to assess changes in the force-velocity profile of specific performance tasks (Jaric, 2016; Pérez-Castilla et al., 2017).

In examining the effect of maximum strength and maximum power training on adult athletes from different sporting backgrounds, the results from Chapter 7 indicate that strength/power athletes obtain superior performance gains compared to endurance athletes in response to performing either a maximum strength or maximum power training block. It is unclear as to the mechanism behind these differences, however previous research has observed the ability of resistance trained versus untrained subjects to produce greater muscle activation during resistance training (Ahtiainen et al., 2003). It is possible that similar difference exists between strength/power and endurance athletes based on their general morphology and training requirements. However, it may also be that the impact of concurrent aerobic training, a major training tool in many endurance sports, has an detrimental effect on high velocity force activities as required in the monitoring tool used in this study (i.e. CMJ) (Wilson, Marin, Rhea, Wilson, Loenneke, & Anderson, 2012).

The final study (Chapter 8) demonstrated that the use of either a CMJ_{BW} or CMJ_{LOAD} will show similar fatigue patterns across multiple successive weeks in AFL players when assessed in-season. Although these two monitoring tests differ in the speed of the contraction with the CMJ_{LOAD} resulting in the concentric contraction taking 15-20% longer than the CMJ_{BW}, this does not appear to influence the fatigue response. Indeed, it may be that the average concentric contraction duration seen in a CMJ_{LOAD} compared with that in a CMJ_{BW} does not alter the resultant fatigue effects. This is supported by the results seen in Chapter 5 where it was noted that faster contraction activities (DJ and sprinting) showed a different fatigue response to the CMJ. Whilst this study (Chapter 5) was performed on adolescent athletes and, not adults, it may be that any lengthening of the CMJ_{BW} contraction time via the addition of an external load will not provide different fatigue information than to what is already provided by this test.

9.2 Practical applications

The various adaptations and responses seen throughout the study suggest that strength and conditioning coaches need to consider the specific structure and scheduling of maximum strength/power training programs and choose the appropriate monitoring tool to monitor these changes across various athlete sub-groups. To enhance the beneficial and limit the detrimental effects of these types of programs, practical applications have been provided for practitioners to aid in the planning and execution of athletic preparation.

Adolescent athletes who have substantial (>2 y) previous resistance training history will display improvements in neuromuscular performance tests from as little as a six-week maximum strength training block. However, these improvements are limited to performance tests of a slower contraction type nature such as the CMJ and are unlikely to be observed in faster contraction type tests such as the DJ or 20-m sprint. When scheduling weekly training for adolescent athletes, the fatigue time course of a maximum strength session will have different time course effects on various neuromuscular movements. Peak force exercises with slow contraction times such as the IMTP recover within four hours of completing the session, as will performance related variables derived from CMJ, whereas fast contraction exercises such as the DJ may suffer from impaired performance for up to 24 h later. These recovery time courses may vary throughout the year with athletes who have performed a pre-season strength training program of at least six weeks, potentially experiencing an attenuated performance decrement and accelerated recovery profile in the CMJ, DJ and 20-m sprint and may even benefit from a quasi, post-activation potentiation effect in the 20-m sprint, 24- and 48-h post a maximum strength session.

Adult athletes who participate in sports requiring substantially different competition and therefore training metabolic demands, e.g. rowing vs sprint cycling, exhibit different performance benefits from similar type maximum strength and power training blocks. In completing either a maximum strength or maximum power block, strength/power athletes such as sprint cyclists show better performance gains compared to their endurance counterparts (rowers). This may impact the duration of a strength training block needed for to gain performance benefits such as improvements in lower body power in rowers.

In monitoring the impact on neuromuscular readiness during a preparation period in an individual based sport, either a CMJ_{BW} or a CMJ_{LOAD} may be used. Within these tests relative peak power may be a more effective monitoring variable than peak force. When monitoring in-season neuromuscular readiness in a weekly-competition team sport, either jump type may be used with both jump height and relative peak power showing good sensitivity to player readiness.

Whether assessing performance changes over a training block or monitoring neuromuscular fatigue, the reliability of each test and its associated variables must also be considered. This study found good reliability for multiple variables across the CMJ, DJ, IMTP and 20-m sprint. However, some variables commonly reported in the literature had either unacceptable reliability such as RFD, whether it was assessed via a CMJ or DJ.

To summarise the practical applications:

1. Adolescents:
   a. A six-week maximum strength training program has beneficial impacts on muscle morphology and multiple neuromuscular performance variables.
   b. Maximum strength training has the largest fatigue effect on DJ performance and less effect on IMTP performance.
   c. Adolescent athletes may be better equipped to deal with the neuromuscular fatigue associated with a maximum strength training session as detected by CMJ, DJ, IMTP and 20 m sprint after performing a six-week strength block.
2. Adult individual sports:
   a. The CMJ_{BW} appears more effective to monitor longitudinal neuromuscular fatigue generated by total training load in a Beach Volleyball athlete than the CMJ_{LOAD} when a taper is included in the monitoring period.
   b. Strength/power athletes show better performance benefits when compared with endurance athletes in both the CMJ_{BW} and CMJ_{LOAD} after four-week maximum-strength and -power training blocks performed during their normal pre-season.
3. Adult team sports:
   a. CMJ_{BW} and CMJ_{LOAD} show similar neuromuscular fatigue responses to the demands of in-season, weekly competition of elite AFL athletes.

9.3 Future research

Topics that warrant further investigation based on the current findings include:

1. Adolescent athlete adaptations and acute response to maximum power training

   a) Chapter 4 showed that adolescent athletes improved morphological, and neuromuscular adaptations to a maximum strength training block performed during a preparation period in their annual training cycle. Chapter 5 highlighted the various acute neuromuscular effects and recovery timelines of adolescent athletes to a maximum strength training session and how this can vary at different times in the annual calendar. Follow-up studies were planned by the authors to expand on these earlier studies; one to investigate the morphological and neuromuscular adaptations to a maximum power training block and another to examine the acute neuromuscular effects and recovery profiles of adolescent athletes to a maximum power training session. However, due to the relocation of the PhD candidate after the completion of the maximum strength training studies this was not possible. Given the use of maximum power training as a common preparation tool it would be interesting to examine these adaptations and acute effects in adolescent athletes.

b) The present study focussed primarily on morphological and neuromuscular adaptations and responses, however as mentioned in the review of literature (Chapter 2), biochemical factors also play a key role in the adaptations and acute responses to training. Subsequently, additional research could investigate the biochemical adaptations and responses of adolescent athletes to the typical maximum strength/power training programs used by strength and conditioning coaches so as to provide an insight into the biochemical responses that may influence performance gains.

2. Adult athletes

a) Chapter 7 highlighted the differences in adaptations between strength/power athletes and endurance athletes when exposed a four-week maximum strength or maximum power training block. However, typical preparation periods usually occur over longer time periods and so it would be interesting to track the strength/power development of both types of athletes over an extended period. Additionally, a larger sample size for this type of study would provide additional statistical power and therefore more confidence in drawing inferences from the findings.

b) The acute neuromuscular readiness of AFL players assessed in-season (Chapter 8) provided a useful introduction into the weekly variations that may be seen. Due to limitations in the scope of this study, no inferences could be made on the relationships to match playing data. Additional research that also tracked relevant game/training data and related this to the strength/power program performed and the neuromuscular readiness of the athlete group across a season would provide additional insight into the interplay of these variables and help practitioners' best monitor the readiness and recovery of their athletes.

9.4 Conclusion

Neuromuscular adaptations to maximum strength and maximum power training in different athlete population groups show similar over-arching responses based on the underpinning acute responses to a single and multiple sessions. However, the magnitude of these adaptations can vary greatly across these different groups, most likely based on the underpinning morphological, biochemical and neuromuscular acute responses. In addition, the time-course of the both the adaptations and acute responses appears different between athletic populations (i.e. adolescents vs adults, endurance vs strength/power) and should be considered when planning an athletes annual cycle. A summary of the major findings from this collection of studies is as follows:

- A preparation period maximum strength block performed in conjunction with sport-specific training improved dynamic strength and CMJ neuromuscular performance whilst also positively impacting on muscle pennation angle in adolescent athletes.
- DJ was the neuromuscular test most susceptible to fatigue, in both magnitude of effects and the time taken to recover, following a maximum strength training session in adolescent athletes.
- Adolescent athletes showed improved neuromuscular fatigue resistance to a maximum strength session after completing a six-week maximum strength block.
- The CMJ_{BW} and CMJ_{LOAD} may both be effective for monitoring neuromuscular readiness/fatigue in adult athletes across the yearly training cycle, however the CMJ_{BW} may provide additional precision during taper periods.
- Strength/power athletes showed better adaptations to both maximum strength and maximum power training blocks when performed in conjunction with their normal sport specific training compared to endurance athletes.

References

Aagaard, P., Andersen, J. L., Dyhre-Poulsen, P., Leffers, A. M., Wagner, A., Magnusson, S. P., . . . Simonsen, E. B. (2001). A mechanism for increased contractile strength of human pennate muscle in response to strength training: changes in muscle architecture. *Journal of Physiology, 534*(2), 613-623.

Aagaard, P., Simonsen, E. B., Andersen, J. L., Magnusson, P., & Dyhre-Poulsen, P. (2002a). Increased rate of force development and neural drive of human skeletal muscle following resistance training. *Journal of Applied Physiology, 93*(4), 1318-1326.

Aagaard, P., Simonsen, E. B., Andersen, J. L., Magnusson, P., & Dyhre-Poulsen, P. (2002b). Neural adaptation to resistance training: changes in evoked V-wave and H-reflex responses. *Journal of Applied Physiology, 92*(6), 2309-2318.

Ahtiainen, J. P., & Häkkinen, K. (2009). Strength athletes are capable to produce greater muscle activation and neural fatigue during high-intensity resistance exercise than nonathletes. *Journal of Strength & Conditioning Research, 23*(4), 1129-1134.

Ahtiainen, J. P., Pakarinen, A., Alen, M., Kraemer, W. J., & Häkkinen, K. (2003). Muscle hypertrophy, hormonal adaptations and strength development during strength training in strength-trained and untrained men. *European Journal of Applied Physiology, 89*(6), 555-563.

Alegre, L. M., Jiménez, F., Gonzalo-Orden, J. M., Martín-Acero, R., & Aguado, X. (2006). Effects of dynamic resistance training on fascicle length and isometric strength. *Journal of Sports Sciences, 24*(05), 501-508.

Alemany, J. A., Pandorf, C. E., Montain, S. J., Castellani, J. W., Tuckow, A. P., & Nindl, B. C. (2005). Reliability assessment of ballistic jump squats and bench throws. *Journal of Strength & Conditioning Research, 19*(1), 33-38.

Andersson, H. M., Raastad, T., Nilsson, J., Paulsen, G., Garthe, I., & Kadi, F. (2008). Neuromuscular fatigue and recovery in elite female soccer: Effects of active recovery. *Medicine and Science in Sports and Exercise, 40*(2), 372-380.

Aragón, L. F. (2000). Evaluation of four vertical jump tests: Methodology, reliability, validity, and accuracy. *Measurement in Physical Education and Exercise Science, 4*(4), 215-228.

Argus, C. K., Gill, N. D., Keogh, J. W., McGuigan, M. R., & Hopkins, W. G. (2012). Effects of two contrast training programs on jump performance in rugby union players during a competition phase. *International Journal of Sports Physiology and Performance, 7*(1), 68-75.

Asçi, A., & Açikada, C. (2007). Power production among different sports with similar maximum strength. *Journal of Strength & Conditioning Research, 21*(1), 10-16.

Baker, D. (2001). The effects of an in-season of concurrent training on the maintenance of maximal strength and power in professional and college-aged rugby league football players. *Journal of Strength & Conditioning Research, 15*(2), 172-177.

Baker, D., Mitchell, J., Boyle, D., Currell, S., Wilson, G., Bird, S., . . . Jones, J. (2011). Resistance training for children and youth: A position stand from the Australian Strength and Conditioning Association (ASCA). 2007.

Baker, D., & Newton, R. U. (2008). Comparison of lower body strength, power, acceleration, speed, agility, and sprint momentum to describe and compare playing rank among professional rugby league players. *Journal of Strength & Conditioning Research, 22*(1), 153-158.

Bartolomei, S., Hoffman, J. R., Merni, F., & Stout, J. R. (2014). A comparison of traditional and block periodized strength training programs in trained athletes. *Journal of Strength & Conditioning Research, 28*(4), 990-997.

Bastiaans, J., Diemen, A., Veneberg, T., & Jeukendrup, A. (2001). The effects of replacing a portion of endurance training by explosive strength training on performance in trained cyclists. *European Journal of Applied Physiology, 86*(1), 79-84.

Beattie, K., Carson, B. P., Lyons, M., & Kenny, I. C. (2016). The effect of maximal- & explosive-strength training on performance indicators in cyclists. *International Journal of Sports Physiology and Performance*, Published ahead of print.

Behm, D. G., Faigenbaum, A. D., Falk, B., & Klentrou, P. (2008). Canadian Society for Exercise Physiology position paper: resistance training in children and adolescents. *Applied Physiology, Nutrition, and Metabolism, 33*(3), 547-561.

Behringer, M., Heede, A. v., Matthews, M., & Mester, J. (2011). Effects of strength training on motor performance skills in children and adolescents: a meta-analysis. *Pediatric Exercise Science, 23*(2), 186-206.

Behringer, M., Neuerburg, S., Matthews, M., & Mester, J. (2013). Effects of two different resistance-training programs on mean tennis-serve velocity in adolescents. *Pediatric Exercise Science, 25*(3), 370-384.

Bennie, J., & Hrysomallis, C. (2005). Resistance training considerations for the sport of squash. *Strength and Conditioning Journal, 27*(3), 30-38.

Bernhardt, D. T., Gomez, J., Johnson, M. D., Martin, T. J., Rowland, T. W., Small, E., . . . Young, J. C. (2001). Strength training by children and adolescents. *Pediatrics, 107*(6), 1470-1472.

Bickel, C. S., Slade, J., Mahoney, E., Haddad, F., Dudley, G. A., & Adams, G. R. (2005). Time course of molecular responses of human skeletal muscle to acute bouts of resistance exercise. *Journal of Applied Physiology, 98*(2), 482-488.

Bompa, T. O. (1999). *Periodization Training for Sports*. Champaign, Il: Human Kinetics.

Bosco, C., Colli, R., Bonomi, R., von Duvillard, S. P., & Viru, A. (2000). Monitoring strength training: neuromuscular and hormonal profile. *Medicine and Science in Sports and Exercise, 32*(1), 202-208.

Brandenburg, J. P., & Docherty, D. (2002). The effects of accentuated eccentric loading on strength, muscle hypertrophy, and neural adaptations in trained individuals. *Journal of Strength & Conditioning Research, 16*(1), 25-32.

Brandon, R., Howatson, G., Strachan, F., & Hunter, A. M. (2015). Neuromuscular response differences to power vs strength back squat exercise in elite athletes. *Scandinavian Journal of Medicine & Science in Sports, 25*(5), 630-639.

Buckthorpe, M., Pain, M. T., & Folland, J. P. (2014). Central fatigue contributes to the greater reductions in explosive than maximal strength with high-intensity fatigue. *Experimental Physiology, 99*(7), 964-973.

Byrne, C., & Eston, R. (2002). The effect of exercise-induced muscle damage on isometric and dynamic knee extensor strength and vertical jump performance. *Journal of Sports Sciences, 20*(5), 417-425.

Campos, G. E., Luecke, T. J., Wendeln, H. K., Toma, K., Hagerman, F. C., Murray, T. F., . . . Staron, R. S. (2002). Muscular adaptations in response to three different resistance-training regimens: specificity of repetition maximum training zones. *European Journal of Applied Physiology, 88*(1), 50-60.

Carroll, T. J., Riek, S., & Carson, R. G. (2002). The sites of neural adaptation induced by resistance training in humans. *Journal of Physiology, 544*(2), 641-652.

Carroll, T. J., Taylor, J. L., & Gandevia, S. C. (2017). Recovery of central and peripheral neuromuscular fatigue after exercise. *Journal of Applied Physiology, 122*(5), 1068-1076.

Chelly, M. S., Fathloun, M., Cherif, N., Amar, M. B., Tabka, Z., & Van Praagh, E. (2009). Effects of a back squat training program on leg power, jump, and sprint performances in junior soccer players. *Journal of Strength & Conditioning Research, 23*(8), 2241-2249.

Chesley, A., MacDougall, J., Tarnopolsky, M., Atkinson, S., & Smith, K. (1992). Changes in human muscle protein synthesis after resistance exercise. *Journal of Applied Physiology, 73*(4), 1383-1388.

Chiu, L. Z., & Barnes, J. L. (2003). The fitness-fatigue model revisited: Implications for planning short-and long-term training. *Strength & Conditioning Journal, 25*(6), 42-51.

Christou, M., Smilios, I., Sotiropoulos, K., Volaklis, K., Pilianidis, T., & Tokmakidis, S. P. (2006). Effects of resistance training on the physical capacities of adolescent soccer players. *Journal of Strength & Conditioning Research, 20*(4), 783-791.

Coelho E Silva, M. J., Figueiredo, A. n. J., Moreira Carvalho, H., & Malina, R. M. (2008). Functional capacities and sport-specific skills of 14- to 15-year-old male basketball players: Size and maturity effects. *European Journal of Sport Science, 8*(5), 277-285.

Comfort, P., Haigh, A., & Matthews, M. J. (2012). Are changes in maximal squat strength during preseason training reflected in changes in sprint performance in rugby league players? *Journal of Strength & Conditioning Research, 26*(3), 772-776.

Cormack, S., Newton, R., McGuigan, M., & Cormie, P. (2008a). Neuromuscular and endocrine responses of elite players during an Australian Rules football season. *International Journal of Sports Physiology and Performance, 3*(4), 439-453.

Cormack, S., Newton, R. U., McGuigan, M. R., & Doyle, T. (2008b). Reliability of measures obtained during single and repeated countermovement jumps. *International Journal of Sports Physiology and Performance, 3*(2), 131-144.

Cormack, S., Newton, R. U., & McGuigan, M. R. M. (2008c). Neuromuscular and endocrine responses of elite players to an Australian Rules football match. *International Journal of Sports Physiology and Performance, 3*(3), 359-374.

Cormie, P., McBride, J. M., & McCaulley, G. O. (2009). Power-time, force-time, and velocity-time curve analysis of the countermovement jump: impact of training. *Journal of Strength & Conditioning Research, 23*(1), 177-186.

Cormie, P., McCaulley, G. O., & McBride, J. M. (2007a). Power versus strength-power jump squat training: Influence on the load-power relationship. *Medicine and Science in Sports and Exercise, 39*(6), 996.

Cormie, P., McCaulley, G. O., Triplett, N. T., & McBride, J. M. (2007b). Optimal loading for maximal power output during lower-body resistance exercises. *Medicine and Science in Sports and Exercise, 39*(2), 340.

Cormie, P., McGuigan, M. R., & Newton, R. U. (2010). Adaptations in athletic performance after ballistic power versus strength training. *Medicine and Science in Sports and Exercise, 42*(8), 1582.

Coutts, A. J., Reaburn, P., Piva, T. J., & Rowsell, G. J. (2007). Monitoring for overreaching in rugby league players. *European Journal of Applied Physiology, 99*(3), 313-324.

Crewther, B., Cronin, J., & Keogh, J. (2006). Possible stimuli for strength and power adaptation. *Sports Medicine, 36*(1), 65-78.

Croix, M. B. A. D. S. (2007). Advances in paediatric strength assessment: Changing our perspective on strength development. *Journal of Sports Science and Medicine, 6*(3), 292-304.

Cronin, J. B., & Hansen, K. T. (2005). Strength and power predictors of sports speed. *Journal of Strength & Conditioning Research, 19*(2), 349.

Damas, F., Phillips, S., Vechin, F. C., & Ugrinowitsch, C. (2015). A review of resistance training-induced changes in skeletal muscle protein synthesis and their contribution to hypertrophy. *Sports Medicine, 45*(6), 801-807.

Dasteridis, G., Piliandis, T., & Mantzouranis, N. (2011). The effect of different strength training programmes on young athletes' sprint performance. *Studies in Physical Culture and Tourism, 18*(2), 141-147.

Drinkwater, E. J., Lawton, T. W., Lindsell, R. P., Pyne, D. B., Hunt, P. H., & McKenna, M. J. (2005). Training leading to repetition failure enhances bench press strength gains in elite junior athletes. *Journal of Strength & Conditioning Research, 19*(2), 382-388.

Dugan, E. L., Doyle, T. L. A., Humphries, B., Hasson, C. J., & Newton, R. U. (2004). Determining the optimal load for jump squats: a review of methods and calculations. *Journal of Strength & Conditioning Research, 18*(3), 668-674.

Duthie, G. M., Pyne, D. B., Ross, A. A., Livingstone, S. G., & Hooper, S. L. (2006). The reliability of ten-meter sprint time using different starting techniques. *Journal of Strength & Conditioning Research, 20*(2), 251.

Faigenbaum, A. D., Kraemer, J. W., Cahill, B., Chandler, J., Dziados, J., Elfrink, L. D., . . . Roberts, S. (1996a). Youth resistance training: Position statement paper and literature review. *Strength and Conditioning Journal, 18*(6), 62-75.

Faigenbaum, A. D., Kraemer, W. J., Blimkie, C. J., Jeffreys, I., Micheli, L. J., Nitka, M., & Rowland, T. W. (2009). Youth resistance training: updated position statement paper from the national strength and conditioning association. *Journal of Strength & Conditioning Research, 23*, S60-S79.

Faigenbaum, A. D., & McFarland, J. (2008). Relative safety of weightlifting movements for youth. *Strength & Conditioning Journal, 30*(6), 23-25.

Faigenbaum, A. D., McFarland, J. E., Keiper, F. B., Tevlin, W., Ratamess, N. A., Kang, J., & Hoffman, J. R. (2007). Effects of a short-term plyometric and resistance training program on fitness performance in boys age 12 to 15 years. *Journal of Sports Science and Medicine, 6*(4), 519-525.

Faigenbaum, A. D., Milliken, L. A., & Westcott, W. L. (2003). Maximal strength testing in healthy children. *Journal of Strength & Conditioning Research, 17*(1), 162-166.

Faigenbaum, A. D., Ratamess, N. A., McFarland, J., Kaczmarek, J., Coraggio, M. J., Kang, J., & Hoffman, J. R. (2008). Effect of rest interval length on bench press performance in boys, teens, and men. *Pediatric Exercise Science, 20*(4), 457-469.

Faigenbaum, A. D., & Schram, J. (2004). Can Resistance Training Reduce Injuries in Youth Sports. *Strength and Conditioning Journal, 26*(3), 16-21.

Faigenbaum, A. D., Westcott, W. L., Micheli, L. J., Outerbridge, A. R., Long, C. J., LaRosa-Loud, R., & Zaichkowsky, L. D. (1996b). The effects of strength training and detraining on children. *Journal of Strength & Conditioning Research, 10*(2), 109-114.

Feldmann, C., Weiss, L., Ferreira, L., Schilling, B., & Hammond, K. (2011). Reactive strength index and ground contact time: Reliability, precision, and association with drop vertical jump displacement. *Journal of Strength & Conditioning Research, 25*, S1.

Flanagan, E. P., Ebben, W. P., & Jensen, R. L. (2008). Reliability of the reactive strength index and time to stabilization during depth jumps. *Journal of Strength & Conditioning Research, 22*(5), 1677.

Fleck, S. J. (1999). Periodized strength training: a critical review. *Journal of Strength & Conditioning Research, 13*(1), 82-89.

Fletcher, I. M., & Jones, B. (2004). The effect of different warm-up stretch protocols on 20 meter sprint performance in trained rugby union players. *Journal of Strength & Conditioning Research, 18*, 885-888.

Foden, M., Astley, S., Comfort, P., McMahon, J., Matthews, M., & Jones, P. (2015). Relationships between speed, change of direction and jump performance with cricket specific speed tests in male academy cricketers. *Journal of Trainology, 4*(2), 37-42.

Folland, J. P., & Williams, A. G. (2007). The adaptations to strength training: Morphological and neurological contributions to increased strength. *Sports Medicine, 37*(2), 145.

Foster, C., Florhaug, J. A., Franklin, J., Gottschall, L., Hrovatin, L. A., Parker, S., . . . Dodge, C. (2001). A new approach to monitoring exercise training. *Journal of Strength & Conditioning Research, 15*(1), 109-115.

Fry, A. C., Kraemer, W. C., Stone, M. H., Koziris, L. P., Thrush, J. T., & Fleck, S. J. (2000). Relationships Between Serum Testosterone, Cortisol, and Weightlifting Performance. *Journal of Strength & Conditioning Research, 14*(3), 338-343.

Gabriel, D. A., Kamen, G., & Frost, G. (2006). Neural adaptations to resistive exercise: Mechanisms and recommendations for training practices. *Sports Medicine, 36*(2), 133.

Gathercole, R. J., Sporer, B. C., Stellingwerff, T., & Sleivert, G. G. (2015a). Comparison of the capacity of different jump and sprint field tests to detect neuromuscular fatigue. *Journal of Strength & Conditioning Research, 29*(9), 2522-2531.

Gathercole, R. J., Stellingwerff, T., & Sporer, B. C. (2015b). Effect of acute fatigue and training adaptation on countermovement jump performance in elite snowboard cross athletes. *Journal of Strength & Conditioning Research, 29*(1), 37-46.

Gee, T. I., Caplan, N., Gibbon, K. C., Howatson, G., & Thompson, K. G. (2016). Investigating the effects of typical rowing strength training practices on strength and power development and 2,000 m rowing performance. *Journal of Human Kinetics, 50*(1), 167-177.

Girard, O., & Millet, G. P. (2008). Neuromuscular fatigue in racquet sports. *Neurologic Clinics, 26*(1), 181-194.

Gonzalez, A. M., Hoffman, J. R., Stout, J. R., Fukuda, D. H., & Willoughby, D. S. (2016). Intramuscular anabolic signaling and endocrine response following resistance exercise: implications for muscle hypertrophy. *Sports Medicine, 46*(5), 671-685.

Gorostiaga, E. M., Izquierdo, M., Iturralde, P., Ruesta, M., & Ibanez, J. (1999). Effects of heavy resistance training on maximal and explosive force production, endurance and serum hormones in adolescent handball players. *European Journal of Applied Physiology & Occupational Physiology, 80*(5), 485-493.

Graham, J. (2002). Periodization research and an example application. *Strength and Conditioning Journal, 24*(6), 62-70.

Guy, J. A., & Micheli, L. J. (2001). Strength training for children and adolescents. *Journal of the American Academy of Orthopaedic Surgeons, 9*(1), 29-36.

Haff, G. G., Carlock, J., Hartman, M. J., Kilgore, J., Kawamori, N., Jackson, J. R., . . . Stone, M. H. (2005). Force-time curve characteristics of dynamic and isometric muscle actions of elite women olympic weightlifters. *Journal of Strength & Conditioning Research, 19*(4), 741-748.

Haff, G. G., Stone, M. H., O'Bryant, H. S., Harman, E. A., Dinan, C., Johnson, R., & Han, K. (1997). Force-time dependent characteristics of dynamic and isometric muscle actions. *Journal of Strength & Conditioning Research, 11*(4), 269-272.

Haines, B., Bourdon, P., & Deakin, G. (2016). Reliability of common neuromuscular performance tests in adolescent athletes. *Journal of Australian Strength and Conditioning, 24*(4), 16-22.

Haines, B., & Deakin, G. (2014). Longitudinal neuromuscular monitoring tool: A case study using bodyweight vs loaded countermovment jump. *Journal of Australian Strength and Conditioning, 22*(5), 37-40.

Hakkinen, K., Kallinen, M., Komi, P. V., & Kauhanen, H. (1991). Neuromuscular adaptations during short-term "normal" and reduced training periods in strength athletes. *Electromyography and Clinical Neurophysiology, 31*(1), 35-42.

Häkkinen, K., & Keskinen, K. (1989). Muscle cross-sectional area and voluntary force production characteristics in elite strength-and endurance-trained athletes and sprinters. *European Journal of Applied Physiology and Occupational Physiology, 59*(3), 215-220.

Hakkinen, K., & Pakarinen, A. (1993). Acute hormonal responses to two different fatiguing heavy-resistance protocols in male athletes. *Journal of Applied Physiology, 74*(2), 882-887.

Hakkinen, K., Pakarinen, A., Alen, M., Kauhanen, H., & Komi, P. V. (1988). Neuromuscular and hormonal adaptations in athletes to strength training in two years. *Journal of Applied Physiology, 65*(6), 2406-2412.

Häkkinen, K., Pakarinen, A., Kraemer, W. J., Häkkinen, A., Valkeinen, H., & Alen, M. (2001). Selective muscle hypertrophy, changes in EMG and force, and serum hormones during strength training in older women. *Journal of Applied Physiology, 91*(2), 569-580.

Hakkinen, K., Pakarinen, A., Kraemer, W. J., Newton, R. U., & Alen, M. (2000). Basal concentrations and acute responses of serum hormones and strength development during heavy resistance training in middle-aged and elderly men and women. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 55*(2), B95-B105.

Hamilton, D. (2009a). Drop jumps as an indicator of neuromuscular fatigue and recovery in elite youth soccer athletes following tournament match play. *Journal of Australian Strength and Conditioning, 17*(4), 3-8.

Hamilton, D. (2009b). Explosive performance in young soccer players during several games in succession: a tournament scenario. *Journal of Australian Strength and Conditioning, 17*, 3-10.

Hansen, K. T., Cronin, J. B., Pickering, S. L., & Newton, M. J. (2011). Does cluster loading enhance lower body power development in preseason preparation of elite rugby union players? *Journal of Strength & Conditioning Research, 25*(8), 2118-2126.

Harries, S. K., Lubans, D. R., & Callister, R. (2012). Resistance training to improve power and sports performance in adolescent athletes: A systematic review and meta-analysis. *Journal of Science and Medicine in Sport, 15*(6), 532-540.

Harries, S. K., Lubans, D. R., & Callister, R. (2015). Systematic review and meta-analysis of linear and undulating periodized resistance training programs on muscular strength. *Journal of Strength & Conditioning Research, 29*(4), 1113-1125.

Harries, S. K., Lubans, D. R., & Callister, R. (2016). Comparison of resistance training progression models on maximal strength in sub-elite adolescent rugby union players. *Journal of Science and Medicine in Sport, 19*(2), 163-169.

Harris, G. R., Stone, M. H., O'Bryant, H. S., Proulx, C. M., & Johnson, R. L. (2000). Short-Term Performance Effects of High Power, High Force, or Combined Weight-Training Methods. *Journal of Strength & Conditioning Research, 14*(1), 14-20.

Hoffman, J. R., Ratamess, N. A., Cooper, J. J., Kang, J., Chilakos, A., & Faigenbaum, A. D. (2005). Comparison of loaded and unloaded jump squat training on strength/power performance in college football players. *Journal of Strength & Conditioning Research, 19*(4), 810-815.

Holm, L., Reitelseder, S., Pedersen, T. G., Doessing, S., Petersen, S. G., Flyvbjerg, A., . . . Kjaer, M. (2008). Changes in muscle size and MHC composition in response to resistance exercise with heavy and light loading intensity. *Journal of Applied Physiology, 105*(5), 1454-1461.

Hopkins, W. G. (2000a). Measures of reliability in sports medicine and science. *Sports Medicine, 30*(1), 1-15.

Hopkins, W. G. (2000b). Reliability from consecutive pairs of trials (Excel spreadsheet). A new view of statistics. .   Retrieved from www.sportsci.org/resource/stats/xrely.xls

Hopkins, W. G. (2006a). Spreadsheets for analysis of controlled trials, with adjustment for a predictor. *Sportscience, 10*, 46-50.

Hopkins, W. G. (2006b). Spreadsheets for analysis of controlled trials, with adjustment for a subject characteristic. *Sportscience, 10*, 46-50.

Hopkins, W. G. (2010). Linear models and effect magnitudes for research, clinical and practical applications. *Sportscience, 14*(1), 49-57.

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise, 41*(1), 3.

Hopkins, W. G., Schabort, E. J., & Hawley, J. A. (2001). Reliability of power in physical performance tests. *Sports Medicine, 31*(3), 211-234.

Hori, N., Newton, R. U., Kawamori, N., McGuigan, M. R., Andrews, W. A., Chapman, D. W., & Nosaka, K. (2008). Comparison of weighted jump squat training with and without eccentric braking. *Journal of Strength & Conditioning Research, 22*(1), 54-65.

Hori, N., Newton, R. U., Kawamori, N., McGuigan, M. R., Kraemer, W. J., & Nosaka, K. (2009). Reliability of performance measurements derived from ground reaction force data during countermovement jump and the influence of sampling frequency. *Journal of Strength & Conditioning Research, 23*(3), 874-882.

Howatson, G., Brandon, R., & Hunter, A. (2016). The Response To, and Recovery From Maximum Strength and Power Training in Elite Track and Field Athletes. *International Journal of Sports Physiology and Performance, 11*(3), 356-362.

Ingle, L., Sleap, M., & Tolfrey, K. (2006). The effect of a complex training and detraining programme on selected strength and power variables in early pubertal boys. *Journal of Sports Sciences, 24*(9), 987-997.

Issurin, V. B. (2010). New horizons for the methodology and physiology of training periodization. *Sports Medicine, 40*(3), 189-206.

Izquierdo, M., Ibanez, J., Hakkinen, K., Kraemer, W. J., Ruesta, M., & Gorostiaga, E. M. (2004). Maximal strength and power, muscle mass, endurance and serum hormones in weightlifters and road cyclists. *Journal of Sports Sciences, 22*(5), 465-478.

James, L. P., Roberts, L. A., Haff, G. G., Kelly, V. G., & Beckman, E. M. (2017). Validity and Reliability of a Portable Isometric Mid-Thigh Clean Pull. *Journal of Strength & Conditioning Research, 31*(5), 1378-1386.

Jaric, S. (2016). Two-load method for distinguishing between muscle force, velocity, and power-producing capacities. *Sports Medicine, 46*(11), 1585-1589.

Johnson, R. B. (1997). Examining the validity structure of qualitative research. *Education, 118*(2), 282-292.

Johnston, M., Cook, C. J., Crewther, B. T., Drake, D., & Kilduff, L. P. (2015). Neuromuscular, physiological and endocrine responses to a maximal speed training session in elite games players. *European Journal of Sport Science, 15*(6), 550-556.

Johnston, M., Cook, C. J., Drake, D., Costley, L., Johnston, J. P., & Kilduff, L. P. (2016). The neuromuscular, biochemical and endocrine responses to a single session verses double session training day in elite athletes. *Journal of Strength & Conditioning Research, 30*(11), 3098-3106.

Jones, D., Rutherford, O., & Parker, D. (1989). Physiological changes in skeletal muscle as a result of strength training. *Quarterly Journal of Experimental Physiology, 74*(3), 233-256.

Kamen, G., & Knight, C. A. (2004). Training-related adaptations in motor unit discharge rate in young and older adults. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 59*(12), 1334-1338.

Kawakami, Y., Abe, T., Kuno, S.-Y., & Fukunaga, T. (1995). Training-induced changes in muscle architecture and specific tension. *European Journal of Applied Physiology and Occupational Physiology, 72*(1-2), 37-43.

Kawamori, N., Rossi, S. J., Justice, B. D., Haff, E. E., Pistilli, E. E., O'Bryant, H. S., . . . Haff, G. G. (2006). Peak force and rate of force development during isometric and dynamic mid-thigh clean pulls performed at various intensities. *Journal of Strength & Conditioning Research, 20*(3), 483-491.

Keiner, M., Sander, A., Wirth, K., Caruso, O., Immesberger, P., & Zawieja, M. (2013). Strength performance in youth: trainability of adolescents and children in the back and front squats. *Journal of Strength & Conditioning Research, 27*(2), 357-362.

Knight, C., & Kamen, G. (2001). Adaptations in muscular activation of the knee extensor muscles with strength training in young and older adults. *Journal of Electromyography and Kinesiology, 11*(6), 405-412.

Kraemer, W. J., Fleck, S. J., Dziados, J. E., Harman, E. A., Marchitelli, L. J., Gordon, S., . . . Triplett, N. (1993). Changes in hormonal concentrations after different heavy-resistance exercise protocols in women. *Journal of Applied Physiology, 75*(2), 594-604.

Kraemer, W. J., Fleck, S. J., & Evans, W. J. (1996). Strength and power training: physiological mechanisms of adaptation. *Exercise and Sport Sciences Reviews, 24*(1), 363-398.

Kraemer, W. J., Fry, A. C., Warren, B. J., Stone, M. H., Fleck, S. J., Kearney, J. T., . . . et al. (1992). Acute hormonal responses in elite junior weightlifters. *International Journal of Sports Medicine, 13*(2), 103-109.

Kraemer, W. J., Gordon, S., Fleck, S., Marchitelli, L., Mello, R., Dziados, J., . . . Fry, A. (1991). Endogenous anabolic hormonal and growth factor responses to heavy resistance exercise in males and females. *International Journal of Sports Medicine, 12*(02), 228-235.

Kraemer, W. J., Häkkinen, K., Newton, R. U., McCormick, M., Nindl, B. C., Volek, J. S., . . . Gordon, S. E. (1998a). Acute hormonal responses to heavy resistance exercise in younger and older men. *European Journal of Applied Physiology and Occupational Physiology, 77*(3), 206-211.

Kraemer, W. J., Häkkinen, K., Newton, R. U., Nindl, B. C., Volek, J. S., McCormick, M., . . . Campbell, W. W. (1999). Effects of heavy-resistance training on hormonal response patterns in younger vs. older men. *Journal of Applied Physiology, 87*(3), 982-992.

Kraemer, W. J., Marchitelli, L., Gordon, S. E., Harman, E., Dziados, J. E., Mello, R., . . . Fleck, S. J. (1990). Hormonal and growth factor responses to heavy resistance exercise protocols. *Journal of Applied Physiology, 69*(4), 1442-1450.

Kraemer, W. J., & Ratamess, N. A. (2004). Fundamentals of resistance training: progression and exercise prescription. *Medicine and Science in Sports and Exercise, 36*(4), 674-688.

Kraemer, W. J., & Ratamess, N. A. (2005). Hormonal responses and adaptations to resistance exercise and training. *Sports Medicine, 35*(4), 339-361.

Kraemer, W. J., Volek, J. S., Bush, J. A., Putukian, M., & Sebastianelli, W. J. (1998b). Hormonal responses to consecutive days of heavy-resistance exercise with or without nutritional supplementation. *Journal of Applied Physiology, 85*(4), 1544-1555.

Kurz, G., Lang, D., Richter, A., & Schwameder, H. (2009). *Reliability of drop jump variations in performance diagnostics.* Paper presented at the ISBS-Conference Proceedings Archive.

Kyröläinen, H., Avela, J., McBride, J. M., Koskinen, S., Andersen, J., Sipilä, S., . . . Komi, P. (2005). Effects of power training on muscle structure and neuromuscular performance. *Scandinavian Journal of Medicine & Science in Sports, 15*(1), 58-64.

Leard, J. S., Cirillo, M. A., Katsnelson, E., Kimiatek, D. A., Miller, T. W., Trebincevic, K., & Garbalosa, J. C. (2007). Validity of two alternative systems for measuring vertical jump height. *Journal of Strength & Conditioning Research, 21*(4), 1296.

Leatherwood, W. E., & Dragoo, J. L. (2012). Effect of airline travel on performance: a review of the literature. *British Journal of Sports Medicine*, bjsports-2012-091449.

Lesinski, M., Prieske, O., & Granacher, U. (2016). Effects and dose–response relationships of resistance training on physical performance in youth athletes: a systematic review and meta-analysis. *British Journal of Sports Medicine, 50*(13), 781-795.

Lillegard, W. A., Brown, E. W., Wilson, D. J., Henderson, R., & Lewis, E. (1997). Efficacy of strength training in prepubescent to early postpubescent males and females: effects of gender and maturity. *Pediatric Rehabilitation, 1*(3), 147-157.

Linnamo, V., Häkkinen, K., & Komi, P. (1997). Neuromuscular fatigue and recovery in maximal compared to explosive strength loading. *European Journal of Applied Physiology and Occupational Physiology, 77*(1-2), 176-181.

Linnamo, V., Newton, R., Häkkinen, K., Komi, P., Davie, A., McGuigan, M., & Triplett-McBride, T. (2000). Neuromuscular responses to explosive and heavy resistance loading. *Journal of Electromyography and Kinesiology, 10*(6), 417-424.

Linnamo, V., Pakarinen, A., Komi, P. V., Kraemer, W. J., & Häkkinen, K. (2005). Acute hormonal responses to submaximal and maximal heavy resistance and explosive exercises in men and women. *Journal of Strength & Conditioning Research, 19*(3), 566-571.

Lloyd, R. S., Faigenbaum, A., Myer, G., Stone, M., Oliver, J., Jeffreys, I., . . . Pierce, K. (2012). UKSCA position statement: Youth resistance training. *Professional Strength and Conditioning, 26*, 26-39.

Lloyd, R. S., Faigenbaum, A. D., Stone, M. H., Oliver, J. L., Jeffreys, I., Moody, J. A., . . . Howard, R. (2014). Position statement on youth resistance training: the 2014 International Consensus. *British Journal of Sports Medicine, 48*, 498-505.

Lloyd, R. S., Oliver, J. L., Hughes, M. G., & Williams, C. A. (2009). Reliability and validity of field-based measures of leg stiffness and reactive strength index in youths. *Journal of Sports Sciences, 27*(14), 1565-1573.

Lyttle, A. D., Wilson, G. J., & Ostrowski, K. J. (1996). Enhancing performance: Maximal power versus combined weights and plyometrics training. *Journal of Strength & Conditioning Research, 10*(3), 173-179.

Malina, R. M. (2006). Weight training in youth-growth, maturation, and safety: An evidence-based review. *Clinical Journal of Sport Medicine, 16*(6), 478-487.

Malina, R. M., Eisenmann, J. C., Cumming, S. P., Ribeiro, B., & Aroso, J. (2004). Maturity-associated variation in the growth and functional capacities of youth football (soccer) players 13–15 years. *European Journal of Applied Physiology, 91*(5-6), 555-562.

McBride, J. M., Triplett-McBride, T., Davie, A., & Newton, R. U. (1999). A comparison of strength and power characteristics between power lifters, olympic lifters, and sprinters. *Journal of Strength & Conditioning Research, 13*(1), 58-66.

McCaulley, G. O., McBride, J. M., Cormie, P., Hudson, M. B., Nuzzo, J. L., Quindry, J. C., & Travis Triplett, N. (2009). Acute hormonal and neuromuscular responses to hypertrophy, strength and power type resistance exercise. *European Journal of Applied Physiology, 105*(5), 695-704.

McGuigan, M. R., Newton, M., & Winchester, J. (2008). Use of isometric testing in soccer players. *Journal of Australian Strength and Conditioning, 16*(4), 11-14.

McGuigan, M. R., Sharman, M. J., Newton, R. U., Davie, A. J., Murphy, A. J., & McBride, J. M. (2003). Effect of explosive resistance training on titin and myosin heavy chain isoforms in trained subjects. *Journal of Strength & Conditioning Research, 17*(4), 645-651.

McGuigan, M. R., & Winchester, J. B. (2008). The relationship between isometric and dynamic strength in college football players. *Journal of Sports Science and Medicine, 7*(1), 101-105.

McGuigan, M. R., Winchester, J. B., & Erickson, T. (2006). The importance of isometric maximum strength in college wrestlers. *Journal of Sports Science and Medicine, 5*(CSSI), 108-113.

McLellan, C. P., Lovell, D. I., & Gass, G. C. (2011). The role of rate of force development on vertical jump performance. *Journal of Strength & Conditioning Research, 25*(2), 379-385.

Meeusen, R., Watson, P., Hasegawa, H., Roelands, B., & Piacentini, M. F. (2006). Central fatigue: the serotonin hypothesis and beyond. *Sports Medicine, 36*(10), 881-909.

Mendez-Villanueva, A., Buchheit, M., Kuitunen, S., Douglas, A., Peltola, E., & Bourdon, P. (2011). Age-related differences in acceleration, maximum running speed, and repeated-sprint performance in young soccer players. *Journal of Sports Sciences, 29*(5), 477-484.

Meylan, C., Cronin, J. B., Oliver, J., Hopkins, W., & Contreras, B. (2014). The effect of maturation on adaptations to strength training and detraining in 11–15-year-olds. *Scandinavian Journal of Medicine & Science in Sports, 24*(3), e156-e164.

Millet, G. P., Candau, R., Fattori, P., Bignet, F., & Varray, A. (2003). VO2 responses to different intermittent runs at velocity associated with VO2max. *Canadian Journal of Applied Physiology, 28*(3), 410-423.

Moir, G., Button, C., Glaister, M., & Stone, M. H. (2004). Influence of familiarization on the reliability of vertical jump and acceleration sprinting performance in physically active men. *Journal of Strength & Conditioning Research, 18*(2), 276.

Moir, G., Garcia, A., & Dwyer, G. (2009). Intersession reliability of kinematic and kinetic variables during vertical jumps in men and women. *International Journal of Sports Physiology and Performance, 4*(3), 317-330.

Monteiro, A. G., Aoki, M. S., Evangelista, A. L., Alveno, D. A., Monteiro, G. A., Piçarro, I. D., & Ugrinowitsch, C. (2009). Nonlinear periodization maximizes strength gains in split resistance training routines. *Journal of Strength & Conditioning Research, 23*(4), 1321-1326.

Moran, J., Sandercock, G. R., Ramírez-Campillo, R., Meylan, C., Collison, J., & Parry, D. A. (2016). A meta-analysis of maturation-related variation in adolescent boy athletes' adaptations to short-term resistance training. *Journal of Sports Sciences, 35*(11), 1-11.

Narici, M. V., Hoppeler, H., Kayser, B., Landoni, L., Claassen, H., Gavardi, C., . . . Cerretelli, P. (1996). Human quadriceps cross-sectional area, torque and neural activation during 6 months strength training. *Acta Physiologica Scandinavica, 157*(2), 175-186.

Newton, R. U., Rogers, R. A., Volek, J. S., Hakkinen, K., & Kraemer, W. J. (2006). Four weeks of optimal load ballistic resistance training at the end of season attenuates declining jump performance of women volleyball players. *Journal of Strength & Conditioning Research, 20*(4), 955-961.

Nuzzo, J. L., Cavill, M. J., Triplett, N. T., & McBride, J. M. (2009). A descriptive study of lower-body strength and power in overweight adolescents. *Pediatric Exercise Science, 21*(1), 34-46.

Ojasto, T., & Hakkinen, K. (2009). Effects of different accentuated eccentric loads on acute neuromuscular, growth hormone, and blood lactate responses during a hypertrophic protocol. *Journal of Strength & Conditioning Research, 23*(3), 946-953.

Østerås, H., Helgerud, J., & Hoff, J. (2002). Maximal strength-training effects on force-velocity and force-power relationships explain increases in aerobic performance in humans. *European Journal of Applied Physiology, 88*(3), 255-263.

Payne, V. G., Morrow Jr, J. R., Johnson, L., & Dalton, S. N. (1997). Resistance training in children and youth: a meta-analysis. *Research Quarterly for Exercise and Sport, 68*(1), 80-88.

Pérez-Castilla, A., Jaric, S., Feriche, B., Padial, P., & García-Ramos, A. (2017). Evaluation of Muscle Mechanical Capacities through the Two-load Method: Optimization of the Load Selection. *Journal of Strength & Conditioning Research*.

Peterson, M. D., Rhea, M. R., & Alvar, B. A. (2005). Applications of the dose-response for muscular strength development: A review of meta-analytic efficacy and reliability for designing training prescription. *Journal of Strength & Conditioning Research, 19*(4), 950-958.

Philippaerts, R. M., Vaeyens, R., Janssens, M., Van Renterghem, B., Matthys, D., Craen, R., . . . Malina, R. M. (2006). The relationship between peak height velocity and physical performance in youth soccer players. *Journal of Sports Sciences, 24*(3), 221-230.

Pikosky, M. A., Faigenbaum, A., Westcott, W., & Rodriguez, N. (2000). Effects of resistance training on protein utilization in healthy children. *Medicine and Science in Sports and Exercise, 34*(5), 820-827.

Pullinen, T., Mero, A., Huttunen, P., Pakarinen, A., & Komi, P. V. (2002). Resistance exercise-induced hormonal responses in men, women, and pubescent boys. *Medicine and Science in Sports and Exercise, 34*(5), 806-813.

Pullinen, T., Mero, A., MacDonald, E., Pakarinen, A., & Komi, P. V. (1998). Plasma catecholamine and serum testosterone responses to four units of resistance exercise in young and adult male athletes. *European Journal of Applied Physiology and Occupational Physiology, 77*(5), 413-420.

Quatman, C. E., Ford, K. R., Myer, G. D., & Hewett, T. E. (2006). Maturation leads to gender differences in landing force and vertical jump performance a longitudinal study. *American Journal of Sports Medicine, 34*(5), 806-813.

Raastad, T., Bjøro, T., & Hallen, J. (2000). Hormonal responses to high-and moderate-intensity strength exercise. *European Journal of Applied Physiology, 82*(1), 121-128.

Raastad, T., Glomsheller, T., Bjøro, T., & Hallén, J. (2001). Changes in human skeletal muscle contractility and hormone status during 2 weeks of heavy strength training. *European Journal of Applied Physiology, 84*(1-2), 54-63.

Raeder, C., Wiewelhove, T., De Paula, S. R., Kellmann, M., Meyer, T., Pfeiffer, M., & Ferrauti, A. (2016). Assessment of fatigue and recovery in male and female athletes following six days of intensified strength training. *Journal of Strength & Conditioning Research, 30*(12), 3412-3427.

Raeder, C., Wiewelhove, T., Westphal-Martinez, M. P., Fernandez-Fernandez, J., De Paula, S. R., Kellmann, M., . . . Ferrauti, A. (2015). Neuromuscular fatigue and physiological responses after five dynamic squat exercise protocols. *Journal of Strength & Conditioning Research, 30*(4), 953-965.

Ramsay, J. A., Blimkie, C. J. R., Smith, K., Garner, S., Macdougall, J. D., & Sale, D. G. (1990). Strength training effects in prepubescent boys. *Medicine and Science in Sports and Exercise, 22*(5), 605-614.

Randell, A. D., Cronin, J. B., Keogh, J. W. L., Gill, N. D., & Pedersen, M. C. (2011). Reliability of performance velocity for jump squats under feedback and nonfeedback conditions. *Journal of Strength & Conditioning Research, 25*(12), 3514-3518.

Remaud, A., Cornu, C., & Guével, A. (2010). Neuromuscular adaptations to 8-week strength training: isotonic versus isokinetic mode. *European Journal of Applied Physiology, 108*(1), 59-69.

Rhea, M. R., & Alderman, B. L. (2004). A meta-analysis of periodized versus nonperiodized strength and power training programs. *Research Quarterly for Exercise and Sport, 75*(4), 413-422.

Rhea, M. R., Ball, S. D., Phillips, W. T., & Burkett, L. N. (2002). A comparison of linear and daily undulating periodized programs with equated volume and intensity for strength. *Journal of Strength & Conditioning Research, 16*(2), 250-255.

Riggs, M. P., & Sheppard, J. M. (2009). The relative importance of strength and power qualities to vertical jump height of elite beach volleyball players during the counter-movement and squat jump. *Journal of Human Sport and Exercise, 4*(3), 221-236.

Roe, G., Darrall-Jones, J., Till, K., Phibbs, P., Read, D., Weakley, J., & Jones, B. (2016). Between-days reliability and sensitivity of common fatigue measures in rugby players. *International Journal of Sports Physiology and Performance, 11*(5), 581-586.

Ronglan, L., Raastad, T., & Børgesen, A. (2006). Neuromuscular fatigue and recovery in elite female handball players. *Scandinavian Journal of Medicine & Science in Sports, 16*(4), 267-273.

Rønnestad, B. R., Kojedal, Ø., Losnegard, T., Kvamme, B., & Raastad, T. (2012). Effect of heavy strength training on muscle thickness, strength, jump performance, and endurance performance in well-trained Nordic Combined athletes. *European Journal of Applied Physiology, 112*(6), 2341-2352.

Sailors, M., & Berg, K. (1987). Comparison of responses to weight training in pubescent boys and men. *Journal of Sports Medicine and Physical Fitness, 27*(1), 30-37.

Samuels, C. H. (2012). Jet lag and travel fatigue: a comprehensive management plan for sport medicine physicians and high-performance support teams. *Clinical Journal of Sport Medicine, 22*(3), 268-273.

Sander, A., Keiner, M., Wirth, K., & Schmidtbleicher, D. (2013). Influence of a 2-year strength training programme on power performance in elite youth soccer players. *European Journal of Sport Science, 13*(5), 445-451.

Santos, E. J., & Janeira, M. A. (2008). Effects of complex training on explosive strength in adolescent male basketball players. *Journal of Strength & Conditioning Research, 22*(3), 903-909.

Schmidtbleicher, D. (1987). Neural adaptation and increase of cross-sectional area studying different strength training methods. *Biomechanics XB, 6B*, 615-620.

Secomb, J. L., Nimphius, S., Farley, O. R., Lundgren, L., Tran, T. T., Parsonage, J., & Sheppard, J. M. (2015). Three weeks cessation from strength training in adolescent athletes increases lower-body isometric strength. *Journal of Australian Strength and Conditioning, 23*(6), 26-29.

Seitz, L. B., Reyes, A., Tran, T. T., de Villarreal, E. S., & Haff, G. G. (2014). Increases in Lower-Body Strength Transfer Positively to Sprint Performance: A Systematic Review with Meta-Analysis. *Sports Medicine, 44*(12), 1693-1702.

Seynnes, O. R., de Boer, M., & Narici, M. V. (2007). Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. *Journal of Applied Physiology, 102*(1), 368-373.

Sheppard, J. M., Cormack, S., Taylor, K. L., McGuigan, M. R., & Newton, R. U. (2008a). Assessing the force-velocity characteristics of the leg extensors in well-trained athletes: The incremental load power profile. *Journal of Strength & Conditioning Research, 22*(4), 1320-1326.

Sheppard, J. M., Cronin, J. B., Gabbett, T. J., McGuigan, M. R., Etxebarria, N., & Newton, R. U. (2008b). Relative importance of strength, power, and anthropometric measures to jump performance of elite volleyball players. *Journal of Strength & Conditioning Research, 22*(3), 758-765.

Sherar, L. B., Esliger, D. W., Baxter-Jones, A. D., & Tremblay, M. S. (2007). Age and gender differences in youth physical activity: does physical maturity matter? *Medicine and Science in Sports and Exercise, 39*(5), 830-835.

Siegler, J., Gaskill, S., & Ruby, B. (2003). Changes evaluated in soccer-specific power endurance either with or without a 10-week, in-season, intermittent, high-intensity training protocol. *Journal of Strength & Conditioning Research, 17*(2), 379-387.

Slinde, F., Suber, C., Suber, L., Edwen, C. E., & Svantesson, U. (2008). Test-retest reliability of three different countermovement jumping tests. *Journal of Strength & Conditioning Research, 22*(2), 640-644.

Smilios, I., Pilianidis, T., Karamouzis, M., & Tokmakidis, S. P. (2003). Hormonal responses after various resistance exercise protocols. *Medicine and Science in Sports and Exercise, 35*(4), 644-654.

Soares, J. M., Mota, P., Duarte, J. A., & Appell, H. J. (1996). Children are less susceptible to exercise-induced muscle damage than adults: a preliminary investigation. *Pediatric Exercise Science, 8*, 361-367.

Spiteri, T., Nimphius, S., Wolski, A., & Bird, S. (2013). Monitoring neuromuscular fatigue in female basketball players across training and game performance. *Journal of Australian Strength and Conditioning, 21*(S2), 73-74.

Stanley, J., D'Auria, S., & Buchheit, M. (2015). Cardiac parasympathetic activity and race performance: an elite triathlete case study. *International Journal of Sports Physiology and Performance, 10*(4), 528-534.

Stone, M. (1993). Position statement: Explosive exercise and training. *Strength & Conditioning Journal, 15*(3), 7-15.

Stone, M., Sanborn, K., O'Bryant, H. S., Hartman, M., Stone, M. E., Proulx, C., . . . Hruby, J. (2003). Maximum strength-power-performance relationships in collegiate throwers. *Journal of Strength & Conditioning Research, 17*(4), 739-745.

Stone, M., Sands, W. A., Pierce, K. C., Carlock, J. O. N., Cardinale, M., & Newton, R. U. (2005). Relationship of maximum strength to weightlifting performance. *Medicine and Science in Sports and Exercise, 37*(6), 1037-1043.

Suchomel, T. J., Nimphius, S., & Stone, M. H. (2016). The importance of muscular strength in athletic performance. *Sports Medicine*, 1-31.

Tanner, R. (2012). *Physiological Tests for Elite Athletes, 2E*: Human Kinetics Publishers.

Taylor, K.-L., Cronin, J., Gill, N., Chapman, D., & Sheppard, J. (2010). Sources of variability in iso-inertial jump assessments. *International Journal of Sports Physiology and Performance, 5*, 546-558.

Tibana, R. A., Prestes, J., da Cunha Nascimento, D., Martins, O. V., De Santana, F. S., & Balsamo, S. (2012). Higher muscle performance in adolescents compared with adults after a resistance training session with different rest intervals. *Journal of Strength & Conditioning Research, 26*(4), 1027-1032.

Tillin, N. A., & Folland, J. P. (2014). Maximal and explosive strength training elicit distinct neuromuscular adaptations, specific to the training stimulus. *European Journal of Applied Physiology, 114*(2), 365-374.

Tillin, N. A., Jimenez-Reyes, P., Pain, M. T., & Folland, J. P. (2010). Neuromuscular performance of explosive power athletes versus untrained individuals. *Medicine and Science in Sports and Exercise*.

Tsolakis, C., Messinis, D., Stergioulas, A., & Dessypris, A. (2000). Hormonal responses after strength training and detraining in prepubertal and pubertal boys. *Journal of Strength & Conditioning Research, 14*(4), 399-404.

Tsolakis, C., Vagenas, G. K., & Dessypris, A. G. (2004). Strength adaptations and hormonal responses to resistance training and detraining in preadolescent males. *Journal of Strength & Conditioning Research, 18*(3), 625-629.

Twist, C., & Highton, J. (2013). Monitoring fatigue and recovery in rugby league players. *International Journal of Sports Physiology and Performance, 8*(5), 467-474.

Uchida, M. C., Aoki, M. S., Navarro, F., Tessutti, V. D., & Bacurau, R. F. P. (2006). Effects of different resistance training protocols over the morphofunctional, hormonal and immunological parameters. *Revista Brasileira de Medicina do Esporte, 12*(1), 21-26.

Veliz, R. R., Requena, B., Suarez-Arrones, L., Newton, R. U., & de Villarreal, E. S. (2014). Effects of 18-week in-season heavy-resistance and power training on throwing velocity, strength, jumping, and maximal sprint swim performance of elite male water polo players. *Journal of Strength & Conditioning Research, 28*(4), 1007-1014.

Viitasalo, J. T., Salo, A., & Lahtinen, J. (1998). Neuromuscular functioning of athletes and non-athletes in the drop jump. *European Journal of Applied Physiology and Occupational Physiology, 78*(5), 432-440.

Vissing, K., Brink, M., Lønbro, S., Sørensen, H., Overgaard, K., Danborg, K., . . . Ringgaard, S. (2008). Muscle adaptations to plyometric vs. resistance training in untrained young men. *Journal of Strength & Conditioning Research, 22*(6), 1799-1810.

Vrijens, J. (1978). Muscle strength development in the pre-and post-pubescent age. *Pediatric Work Physiology* (Vol. 11, pp. 152-158). Basel: Karger Publishers.

Walker, S., Davis, L., Avela, J., & Häkkinen, K. (2012). Neuromuscular fatigue during dynamic maximal strength and hypertrophic resistance loadings. *Journal of Electromyography and Kinesiology, 22*(3), 356-362.

Walmsley, R. P., & Amell, T. K. (1996). The application and interpretation of intraclass correlations in the assessment of reliability in isokinetic dynamometry. *Isokinetics and Exercise Science, 6*(2), 117-124.

Wang, R., Hoffman, J. R., Tanigawa, S., Miramonti, A. A., La Monica, M. B., Beyer, K. S., . . . Jeffrey, S. R. (2016). Isometric mid-thigh pull correlates with strength, sprint and agility performance in collegiate rugby union players. *Journal of Strength & Conditioning Research, 30*(11), 3051-3056.

Wernbom, M., Augustsson, J., & Thomeé, R. (2007). The influence of frequency, intensity, volume and mode of strength training on whole muscle cross-sectional area in humans. *Sports Medicine, 37*(3), 225-264.

Wiewelhove, T., Raeder, C., Meyer, T., Kellmann, M., Pfeiffer, M., & Ferrauti, A. (2015). Markers for routine assessment of fatigue and recovery in male and female team sport athletes during high-intensity interval training. *PloS one, 10*(10), 1-17.

Wilson, J. M., Marin, P. J., Rhea, M. R., Wilson, S. M., Loenneke, J. P., & Anderson, J. C. (2012). Concurrent training: a meta-analysis examining interference of aerobic and resistance exercises. *Journal of Strength & Conditioning Research, 26*(8), 2293-2307.

Winchester, J. B., Erickson, T. M., Blaak, J. B., & McBride, J. M. (2005). Changes in bar-path kinematics and kinetics after power-clean training. *Journal of Strength & Conditioning Research, 19*(1), 177-183.

Winchester, J. B., McBride, J. M., Maher, M. A., Mikat, R. P., Allen, B. K., Kline, D. E., & McGuigan, M. R. (2008). Eight weeks of ballistic exercise improves power independently of changes in strength and muscle fiber type expression. *Journal of Strength & Conditioning Research, 22*(6), 1728-1734.

Zafeiridis, A., Smilios, I., Considine, R. V., & Tokmakidis, S. P. (2003). Serum leptin responses after acute resistance exercise protocols. *Journal of Applied Physiology, 94*(2), 591-597.

Zatsiorsky, V. M., & Kraemer, W. J. (2006). *Science and Practice of Strength Training*. Champaign, IL: Human Kinetics.

Appendix 1 – Ethics approval

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Appendix 2 – Permission for print

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Appendix 3 – Conference Proceedings

Body composition, morphological and neuromuscular adaptations to strength training in adolescent male athletes

Bourdon, P., Haines., & Deakin, G. (2016). Body composition, morphological and neuromuscular adaptations to strength training in adolescent male athletes. *Medicine & Science in Sports & Exercise*, 48(5S1), 987

Monitoring the effects of maximum strength training programs conducted at various times in the periodized training cycle has been well documented in adult athletes, however, research on adolescent athletes is scarce.

Purpose: The purpose of this study was to examine the effects of strength training at different periods in the annual training cycle on body composition, muscle morphology and neuromuscular performance in adolescent athletes.

Methods: Fourteen young male athletes (age 16.5 ± 1.1 y, height 171.3 ± 6.3 cm, body mass 65.0 ± 11.2 kg) performed a battery of tests before and after two specific strength training blocks; in-season and preparatory period. Tests included a DEXA whole-body scan, ultrasound of the vastus lateralis (VL), countermovement jump (CMJ), drop jump (DJ), isometric mid-thigh pull (IMTP), 20 m sprint and 3RM back squat. Meaningful differences following each training period were assessed using a magnitude-based inferences approach (effect sizes [ES]) with qualitative descriptors of change also calculated.

Results: Body composition showed trivial changes throughout both study periods. VL muscle thickness increased during the preparatory period (7.5% ± 3.3%). The CMJ variables showed no positive effects during the in-season period, however increases were seen in several of these variables during the preparatory period (e.g., jump height = 4.9% ± 3.1%; peak concentric power 5.3% ± 5.9%). Most DJ variables decreased during both training periods whilst IMTP measures showed improvements during the in-season period but remained stable during the preparatory period. Most 20 m sprint variables showed positive effects (e.g., 5 m split = 5.0% ± 4.7%) following the in-season period but no clear changes during the preparatory period. 3RM back squat showed a small increase following in-season training (7.5% ± 4.5%) and an even greater increase during the preparatory period (16.9% ± 5.2%).

Conclusion: This study found that in adolescent male athletes a specific preparatory period strength program will likely result in greater improvements in dynamic lower body strength/power measures compared to one conducted in-season. In-season strength training may however have a more beneficial impact on sport specific physical performance variables such as sprint speed.