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**A BIOMECHANICAL INVESTIGATION OF  
CONTEMPORARY POWERLIFTING TRAINING  
PRACTICES AND THEIR POTENTIAL  
APPLICATION TO ATHLETIC DEVELOPMENT**

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## **PUBLICATIONS AND PRESENTATIONS**

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### **Published peer reviewed articles**

Swinton, P.A. Lloyd, R. Keogh, W.J.H. Argouris, I. Stewart, A.D (2012) A biomechanical comparison of the traditional squat, powerlifting squat and box squat. *Journal of Strength & Conditioning Research*, 26(7):1805-18016

Swinton, P.A. Stewart, A.D. Lloyd, R. Argouris, I. Keogh, W.J.H (2012) Effect of load positioning on the kinematics and kinetics of weighted vertical jumps. *Journal of Strength & Conditioning Research*, 26(4):906-913.

Swinton, P.A. Stewart, A.D. Keogh, W.J.H. Argouris, I. Lloyd, R. (2011) Kinematic and kinetic analysis of maximal velocity deadlifts performed with and without the inclusion of chain resistance. *Journal of Strength & Conditioning Research*, 25(7):2000-2009.

Swinton, P.A. Stewart, A.D. Keogh, W.J.H. Argouris, I. Lloyd, R. (2011) A biomechanical analysis of straight and hexagonal barbell deadlifts using submaximal loads. *Journal of Strength & Conditioning Research*, 25(7):2000-2009.

Swinton, P.A. Lloyd, R. Argouris, I. Stewart, A.D (2009) Contemporary training practices in elite British powerlifters: Survey results from an international competition. *Journal of Strength & Conditioning Research*, 23(2):380-384.

### **Peer-reviewed articles currently under review**

Swinton, P.A. Lloyd, R. Keogh, W.J.H. Argouris, I. Stewart, A.D (2012) Predictor models of sprint, vertical jump and change of direction performance. *Journal of Strength & Conditioning Research*, Submitted – in second review

## **Conference proceedings**

Lloyd, R. Stewart, A.D. Agouris, I. Keogh, J.W.L. Swinton, P.A. (2012) Biomechanical comparison of the deadlift and power clean performed explosively with sub-maximum loads. VIII International Conference on Strength Training. OSLO (in Press).

Swinton, P.A. Lloyd, R. Agouris, I. Keogh, J.W.L. Stewart, A.D. (2012) A Biomechanical Comparison of the Traditional Squat, Powerlifting Squat and Box Squat. ICSEMIS. Glasgow (in Press).

Swinton, P.A. Lloyd, R. Agouris, I. Keogh, J.W.L. Stewart, A.D. (2012) The Relationship Between Physiological and Anthropometric Measures and Indicators of Athletic Performance. ICSEMIS. Glasgow (in Press).

Swinton, P.A. Agouris, I. Lloyd, R. Stewart, A. Keogh, J.W.L. (2010) Effect of load positioning on the kinematics and kinetics of weighted jumps. XXVIII International Symposium of Biomechanics in Sports. 563 – 566.

Swinton, P.A. Agouris, I. Lloyd, R. Stewart, A. Keogh, J.W.L. (2010). Effect of increasing vertical centre of mass displacement on biomechanical stimulus of traditional resistance training exercises. XXVIII International Symposium of Biomechanics in Sports. 598 – 601.

## **Seminars**

Swinton, P.A. Contemporary training practices of powerlifters. (2010) Scottish Universities Sport Conference. Aberdeen.

## ABBREVIATIONS LIST

---

|       |                                    |
|-------|------------------------------------|
| 1RM   | One repetition maximum             |
| ANOVA | Analysis of Variance               |
| ASIS  | Anterior Superior Iliac Spine      |
| COM   | Centre of mass                     |
| EMG   | Electromyography                   |
| EMS   | Electromyostimulation              |
| ERT   | Explosive resistance Training      |
| GCRS  | Global Cartesian Reference System  |
| GRF   | Ground reaction force              |
| HBD   | Hexagonal barbell deadlift         |
| IAP   | Intra abdominal pressure           |
| ICC   | Intraclass correlation coefficient |
| LCRS  | Local Cartesian Reference Systems  |
| PAP   | Postactivation potentiation        |
| RFD   | Rate of force development          |
| RM    | repetition maximum                 |
| ROM   | Range of motion                    |
| SBD   | Straight barbell deadlift          |
| SSC   | Stretch shortening cycle           |
| VGRF  | Vertical ground reaction force     |

## GLOSSARY

---

|                                 |   |
|---------------------------------|---|
| ATPase                          | A class of enzymes that catalyse the decomposition of adenosine triphosphate (ATP) into adenosine diphosphate (ADP) and a free phosphate ion. |
| Ballistic exercise              | An exercise where the body and/or the external resistance are projected into space at the end of the movement                                 |
| Clean                           | An exercise where the barbell is lifted from the floor to the clavicles in a single motion.   |
| General athletes                | For the purposes of this project are defined as sportsmen and women other than strength athletes  |
| Lactate threshold               | The exercise intensity at which lactate begins to accumulate in the blood stream  |
| Plyometric exercise             | An exercise that incorporates a rapid transition between eccentric and concentric phases  |
| Rate of force development       | time derivative of force data   |
| Snatch                          | An exercise where the barbell is lifted from the floor to above the head in a single motion   |
| Speed-strength                  | The ability to overcome relatively light loads at fast velocities   |
| Strength-speed                  | The ability to overcome relatively heavy loads at fast velocities   |
| Strength Sports                 | A collection of sports that require almost exclusive engagement with resistance training to be successful.                                    |
| Traditional resistance exercise | A multi-joint resistance exercise characteristic of those conventionally used by powerlifters   |
| $\dot{V}O_2\text{max}$          | A measure of the maximum amount of oxygen a person can extract from the atmosphere and then transport and use in tissues                      |
| Weightlifting                   | Also referred to as Olympic weightlifting, an athletic discipline performed in the modern Olympics  |
| Weightraining                   | Physical activity that incorporates the use of external resistance sources  |

## ABSTRACT

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The contemporary training practices of powerlifters are presently being adopted by athletes from a variety of sports seeking to improve their performance. The aims of this PhD were to: 1) identify the contemporary training practices of powerlifters; 2) investigate the biomechanical stimulus the training practices create; and 3) assess whether the training practices have the potential to improve the athletic performance of general athletes

The aims were achieved through the completion of five related studies. The first study employed questionnaires and interviews to identify the contemporary training practices used by elite powerlifters. The results demonstrated that elite powerlifters used a wide variety of training practices, many of which would not have been attributed to the group based on previous literature. The practices were categorised based on their underlying mechanical principles so that the essential features could be investigated in the subsequent studies. A regression-based approach was used in the second study to identify the biomechanical variables associated with performance of common sporting tasks. Maximum force production, power, velocity and rate of force development (RFD) were shown to explain a large percentage of variation in performance of tasks such as sprinting, jumping and changing direction (adjusted  $R^2$  ranged from 0.43 to 0.86). These mechanical variables were then measured in a series of experimental studies to assess the potential of the contemporary powerlifting practices to improve athletes' physical performance. Assessments were based on a central paradigm in strength and conditioning that asserts that improvements in the ability to express biomechanical variables (e.g. force and power) are best obtained with training practices that maximise acute production of the same variable.

Based on the categorisation of the mechanical principles underlying the assessed training practices, three experimental studies were conducted that investigated: 1) the practice of performing traditional resistance exercises at maximum velocity; 2) the effects of manipulating the external resistance through the use of variable resistance material (chain resistance) and an unconventional barbell (the hexagonal barbell); and 3) the effects of altering the movement strategy used to perform the squat. The results of the studies clearly demonstrated that each of the practices investigated could be used to substantially alter and in most cases enhance the biomechanical stimulus created. The practice of performing

traditional resistance exercises at maximum velocity revealed that all key mechanical variables were significantly increased ( $p < 0.05$ ) compared with the standard practice of performing repetitions with a sub-maximum velocity. In addition, the results demonstrated that when performing a traditional resistance exercise such as the deadlift at maximum velocity, experienced resistance trained athletes could accelerate the load for the majority (75% to 90%+) of the movement.

The second experimental study featuring the separate use of chain resistance and the hexagonal barbell to alter the characteristics of the external resistance demonstrated contrasting effects. The change in position of the external resistance when using the hexagonal barbell significantly ( $p < 0.05$ ) increased the participants' ability to produce high force, power, velocity and RFD values across a range of loads in comparison with the same movement performed with a traditional straight barbell. In contrast, the results from the study evaluating the effects of adding chain resistance showed that whilst force values were increased with the addition of chains, velocity, power and RFD values substantially decreased compared to standard repetitions performed with barbell resistance only. The results also demonstrated that the effects of the chain resistance were more noticeable with heavier chain and barbell loads.

The final experimental investigated the effects of altering the movement strategy used to perform the back squat exercise. The results confirmed that changes to the movement strategy had a significant effect on a range of kinematic and kinetic variables. In particular, the contemporary techniques promoted by powerlifters resulted in substantial kinematic and kinetic changes at the hip and reduced kinetic output at the ankle joint.

Collectively, the work from this PhD supports the selective use of contemporary powerlifting training practices for the development of athletic potential. Future research should build on the framework created in this thesis, progressing to longitudinal and ultimately implementation studies to increase the likelihood of transferring the results to practice.

## CHAPTER 1. INTRODUCTION

---

The sport of powerlifting has become one of the most popular disciplines in a collection of modern day activities commonly referred to as strength sports. Alongside other disciplines, such as bodybuilding, strongman and Olympic weightlifting, powerlifting requires participants to engage extensively with resistance training to develop specific aspects of fitness. Of all the strength sports, powerlifting is viewed as the discipline which requires competitors to exhibit the highest maximum strength capabilities. The training practices and subsequent phenotypes developed by powerlifters have been used infrequently as a model for researchers to investigate topics such as the joint loading capacity of the human body (Escamilla 2001, Nisell and Ekholm 1986, Cholewicki, McGill and Norman 1991), the role of ageing in physical decline (Anton, Spiriduso and Tanaka 2004, Galloway, Kadoko and Joki 2002), and the long-term adaptive response of physiological systems to strenuous resistance exercise (Hurley et al. 1987, Fry 2004, Walters, Jezequel and Grove 2012). The results from powerlifting competitions have also been used to model the relationship between strength and body mass (Cleather 2006, Markovic and Sekulic 2006). As these results have consistently demonstrated strong positive relationships between competition performance and body mass, some researchers have suggested that powerlifting is a sport mainly concerned with inducing muscular hypertrophy (Hakkinen, Alen and Komi 1984). However, more detailed and widely accepted models of maximum strength propose that the central and peripheral nervous systems (including innervations, signalling and synchronisation) act in combination with muscle cross-sectional area to determine force output (Kraemer, Fleck and Evans 1996). These latter models have greatly influenced understanding of the demands of powerlifting and the training strategies used by competitors.

More recently, the performance of powerlifters has been described from the perspective of complex systems (Manso-Garcia et al. 2008). Using this perspective, results achieved by powerlifters can be attributed to the internal structure of the sport as a whole, and not solely to the competitor's characteristics. Complex systems in general are characterised by arrangements of interacting elements whose collective result is not determined by simple linear combinations of the individual behaviours (Zimmer 1999). Importantly, many complex systems adapt to changes in the environment without the need of a central controller or single regulatory body. Applied to the sport of powerlifting, a complex systems perspective

emphasises that performances will be influenced by factors such as the overall quality and size of competitions, the degree of professionalism in the sport, incentives provided, and advances in relevant technology. It is within this wider context that recent changes in various elements of powerlifting can be understood to have substantially impacted the sport as a whole. An important example of these recent changes is the proliferation of internet sites dedicated to powerlifting, which appears to have acted as a catalyst to expand participant numbers and increase professionalism of the sport through enhanced revenue from sponsorship.

The proliferation of internet sites dedicated to powerlifting also appears to have influenced the training methods adopted by the athletes. Previous descriptions of the training methods employed by powerlifters have focused on their use of heavy loads and exercises similar to those performed in competition (Fry 2004). However, novel and diverse training practices have been promoted through internet sources over the last decade. A collection of these training methods have gained acceptance and now appear widespread in their use. Examples include the use of unconventional barbells, the performance of sled dragging exercises and the inclusion of variable resistance in the form of chains and bands. The expansion of training methods employed by powerlifters has only recently been acknowledged by researchers in the area of sport and exercise science (Chiu, Moore and Favre 2007). This recognition is primarily the result of observing athletes from mainstream sports adopting the same practices. Whilst researchers have begun to investigate isolated features of the contemporary training practices developed and used by powerlifters, currently no systematic effort to investigate potential efficacy has been presented. This PhD represents the initial stages of a larger research project with the goal of addressing this issue. The aims of the PhD are to identify the contemporary training practices used by powerlifters, and to provide a detailed analysis of the biomechanical stimulus created. By determining which mechanical variables are closely related to performance of important sporting tasks, a third central aim of the PhD is to assess whether the practices selected could provide appropriate mechanical stimuli for athletes of other sports.

The scientific investigation of any training practice requires extensive study employing a range of methodological approaches. The collective aim of applied sport science research should ultimately be the improvement of athletes' performance. However, it has been highlighted that sport science research is poorly translated into practices used by athletes (Haff et al. 2010, Bishop et al. 2006). It has been noted that a disconnect between

researchers and practitioners occurs as a result of factors such as conservative coaching practices, the overly theoretical and non-applied nature of problems investigated by many researchers, and decisions to disseminate information in highly specialised scientific journals (Bishop et al. 2006, Stone, Sands and Stone 2004). It has also been suggested that a principal limitation in terms of the transfer of knowledge is a lack of structure surrounding research and its progression (Bishop 2008). Recently, Bishop (2008) proposed an applied research model to improve the transfer of sports science research to practice. The model describes multiple phases that progress research designs from descriptive to experimental, to implementation based. The model also emphasises the importance of meta-analyses across the phases, and execution of well designed studies in the initial descriptive stages to underpin the research that follows (Bishop 2008).

The conception and design of this PhD was completed prior to the publication of Bishop's (2008) model. However, independently, the structure of this PhD closely matches the initial phases proposed (see Figure 1.1). The first phase consists of defining the research problem and providing context. The research problem investigated here was driven by the need to provide coaches and athletes with information regarding popular, but untested training practices. The context of the PhD is discussed in greater depth in chapter two, with discussion of the theoretical frameworks underpinning the research provided. The second stage of the research process comprises descriptive research to identify which training practices from those promoted were used by successful powerlifters (chapter three). Once these were established, the biomechanical variables that could predict performance in common sporting tasks were investigated (chapter four). This information was used to determine the variables measured in the experimental studies. The three dimensional biomechanical model used to calculate kinematics and kinetics of the body is presented in chapter five. The subsequent three chapters include the experimental studies of training practices identified earlier in the thesis. The training practices were categorised based on their underlying mechanical premise so that more general conclusions regarding the stimulus created could be drawn (chapters six to eight). The final chapter comprises a summary of the work, general conclusions, and recommendations for future research based on completion of the model outlined by Bishop (2008) in attempts to maximise the likelihood of findings transferring to practice.

**Figure 1.1:** Schematic outline of the applied research model for the sport sciences and corresponding thesis chapters

|                 | Stage |  | Location within thesis |
|-----------------|-------|--|------------------------|
| Description     | 1     | Defining problem, providing context        | → Chapters 1 & 2       |
|                 | 2     | Descriptive research                       | → Chapter 3            |
|                 | 3     | Predictors of performance                  | → Chapter 4            |
| Experimentation | 4     | Experimental testing of predictors         | → Chapters 6, 7 & 8    |
|                 | 5     | Determinants of key performance predictors |                        |
|                 | 6     | Efficacy studies                           |                        |
|                 | 7     | Barriers to uptake                         |                        |
| Implementation  | 8     | Implementation studies                     |                        |

Adapted from: Bishop, D. (2008). An applied research model for the sport sciences. *Sports Medicine*. 38(3): pg 255.

## **CHAPTER 2. LITERATURE REVIEW**

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This literature review aims to provide background for the work conducted in this project and present a clear rationale for the overall direction taken in this thesis. This will be achieved by firstly providing an overview of: (a) resistance training; (b) the models used to design and investigate specific practices; and (c) the potential for resistance training to improve sports performance. Secondly, by discussing strength athletes and the potential relevance of their training practices in the physical preparation of others. Thirdly, by outlining and critiquing biomechanics as a field of study to provide lines of evidence that can be used to improve the overall effectiveness of resistance training.

### **2.1 Resistance training**

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#### **2.1.1 Introduction to resistance training**

The term resistance training has been used in the sport and medical literature to describe training modalities ranging from the use of free weights and resistance machines to plyometrics, climbing and hill running (Stratton et al. 2004, Kraemer and Fleck 2004, Faigenbaum 2007). Frequently, the term is used interchangeably with 'strength training' and 'weight training' to refer to practices that incorporate external loads with the goal of increasing muscular strength (Kraemer and Fleck 2004, Stone, Stone and Sands 2007). However, defining and delimiting resistance training is an important process when conducting research. If the range of training modalities considered is too diverse, then it is difficult to generalise findings from studies. Conversely, limiting the term resistance training to the development of maximum strength fails to acknowledge an extensive research base that has demonstrated the potential to elicit an array of physiological adaptations that enhance multiple fitness and health parameters (Gordon et al. 2009, Cornelissen and Fagard 2005, American College of Sports Medicine 2009). For the purposes of this research project, resistance training will be defined as:

*A mode of training that requires skeletal muscles to produce force against an external resistance source.*

In this context, resistance training is recognised as force training with magnitude, duration and temporal characteristics highly dependent upon the effort applied and the specific nature of the external resistance source.

The study of resistance training is a relatively new area of sport and medical research. Historically, studies on the use of exercise for health or performance have centred on aerobic activities and their effects on the cardiovascular system (Peterson, Rhea and Alvar 2004). The first study to investigate the effects of a systematic form of resistance training using barbells and dumbbells was conducted by Delorme (1945). Based on clinical observations of 300 patients with muscular atrophy, Delorme (1945) reported that the use of resistance exercises with progressively increasing loads improved muscle size and strength. Delorme (1945) also observed that the greatest increases in strength occurred when a heavy resistance was combined with a low number of repetitions, whereas muscular endurance was best improved by performing a high number of repetitions with a light resistance. The observations made by Delorme (1945) formed the basis of the overload principle and the principle of specificity which influences the design of all contemporary resistance training programmes (Stone, Stone and Sands 2007).

Following the seminal research conducted by Delorme (1945), further refinement of resistance training design was delayed until the 1960s, where researchers employed various longitudinal designs to systematically manipulate different training variables (Berger 1962b, Hellebrant and Houtz 1956, Berger 1962a, Berger 1965, Capen 1950, O'Shea 1966). Consistent demonstration that resistance training could enhance muscular strength and endurance in heterogeneous populations led researchers to elucidate many of the adaptive responses of the musculoskeletal (McDonagh and Davies 1984, Clarke 1973, Caiozzo, Perrine and Edgerton 1981), nervous (Edström and Grimby 1986, Sale 1988, Costill et al. 1979), and endocrine (Kraemer 1988, Guezennec et al. 1986, Hetrick and Wilmore 1979) systems.

Wider appreciation of the potential benefits of resistance training in the scientific community was limited by the belief that functional improvements were restricted to muscular strength and endurance, and that these variables played a limited role in the general population's health. Indeed, initial guidelines for the prescription of population-level physical activity

stated that individuals need only perform aerobic exercise (American College of Sports Medicine 1978). At the time these guidelines were published, there were no clear distinctions between the uses of exercise for fitness as opposed to health (American College of Sports Medicine 1998). In addition, epidemiological research reported strong relationships between aerobic endurance activities and the prevention of cardiovascular disease (Fox and Skinner 1964, Kannel 1970). As a result, the ability of aerobic activities to increase  $\dot{V}O_2\text{max}$  was interpreted as a means of improving health (Blair, LaMonte and Nichaman 2004). As physical activity guidelines shifted from an exclusively “performance-related fitness” paradigm to one that acknowledged the multifaceted dimensions of health, researchers began to recognise the benefits of resistance training as a means of improving health-related factors such as functional capacity, basal metabolism, bone mineral density and low back health (Feigenbaum and Pollock 1999). Subsequent health-related guidelines began to incorporate resistance training as part of an integrated physical activity regime that also featured aerobic and various other exercise modalities (McSwegan et al. 1989, American College of Sports Medicine. 1990, American Association of Cardiovascular and Pulmonary Rehabilitation. 1999 , Fletcher et al. 1995). In the last decade, research investigating the health related benefits of resistance training has increased dramatically, with findings revealing that the unique mechanical and physiological stimulus has the potential to improve blood pressure (Cornelissen and Fagard 2005), metabolic health (Gordon et al. 2009), weight control (Schmitz et al. 2003, Hunter et al. 2002), and psychological well-being (Penedo and Dahn 2005). It is likely that future research will focus on optimising resistance training strategies for different health conditions whilst ensuring compliance remains high.

### **2.1.2 Resistance training models**

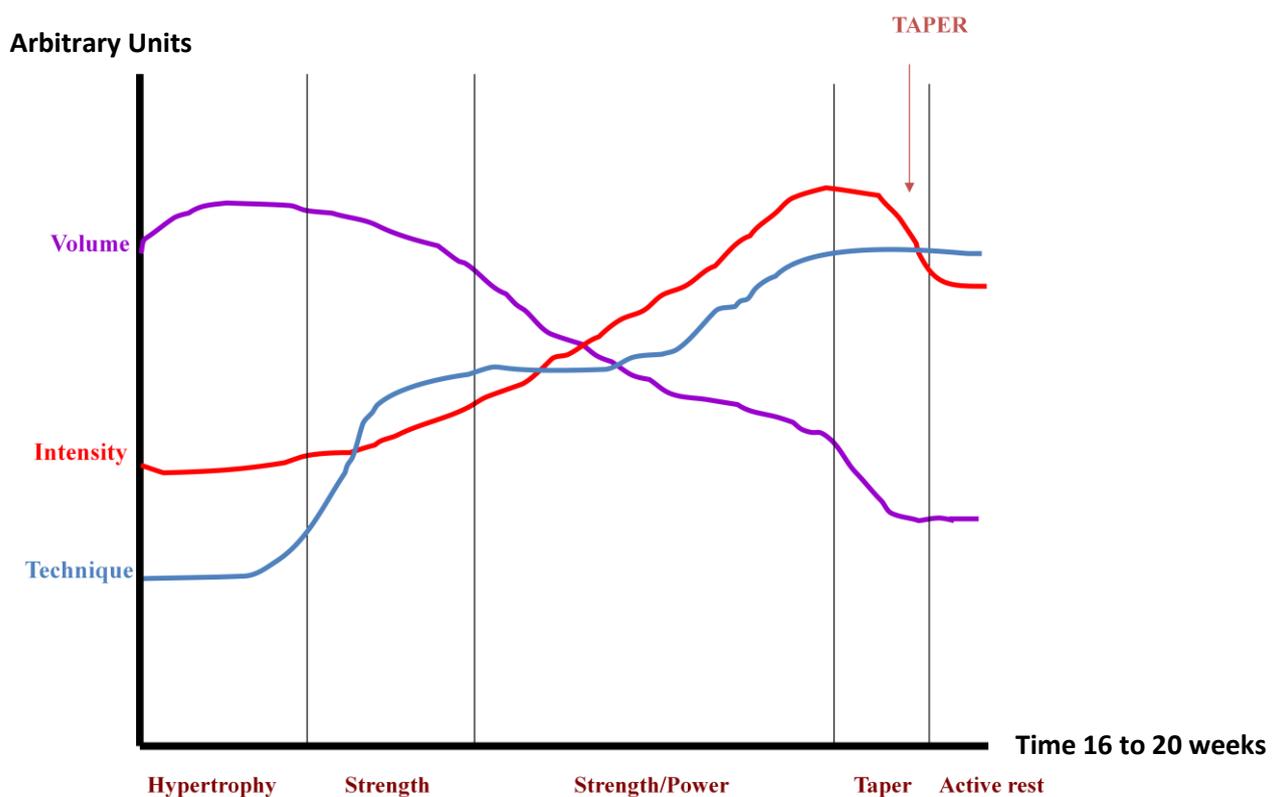
To effectively design and investigate resistance training programmes an appropriate theoretical framework is required. A number of models with various degrees of overlap have been developed (Siff 2003, Verkhoshansky 1986, Bird, Tarpenning and Marino 2005, Kraemer 1983a, Issurin 2008). These models have originated from the perspective of enhanced sports performance and subsequent discussions of resistance training in this literature review will correspond primarily with this perspective. The model most commonly used in peer reviewed research is the acute variable model first proposed by Kraemer (1983a, 1983b). The first stage of the model comprises a needs analysis to identify the important muscle groups, energy systems and specific fitness characteristics (e.g. muscle strength, hypertrophy, power, body composition) that require development (Kraemer and

Fleck 2004, Kraemer 1983a). Once the needs analysis is completed, a long-term resistance training programme is designed based on the manipulation of selected variables. Kraemer (1983a) originally identified four acute programme variables that he considered to uniquely define the stimulus of a single training session. The four variables identified were load intensity, exercise selection, length of rest periods and the order that exercises were performed. Since its inception, the model has been amended to include the number of sets performed and repetition velocity to create a total of six acute programme variables (Kraemer and Fleck 2004). A large number of cross-sectional studies have investigated the short-term effects of manipulating different combinations of the variables identified by Kraemer (Kraemer et al. 1990, Ahtiainen et al. 2005) (Matuszak et al. 2003, Abdessemed et al. 1999) Results have consistently demonstrated that manipulation significantly alters the associated mechanical, metabolic and hormonal stimulus. Importantly, longitudinal studies have demonstrated that changes in short-term effects from manipulation of the variables can accumulate to alter the training response and development of fitness parameters over the long-term (Krieger 2009, Jones et al. 1999, de Salles et al. 2010).

The combined manipulation of six acute programme variables that can each adopt a wide range of values provides an almost unlimited number of possible training sessions. To create adaptations over the long-term many successive training sessions, each providing an overload effect, must be undertaken. The strategic planning and variation of training over extended periods is commonly referred to as periodization and is generally conceptualised based on the training model selected. When training is designed using the acute variable model, periodization is viewed as the systematic long-term manipulation of the featured variables (Kramer and Fleck 2004). In classical strength/power periodization models, the training cycle commences with sessions comprising high volumes and low intensities and gradually progresses to sessions comprising the reverse (low volumes and high intensities) (Kramer and Fleck 2004). To achieve this change in stimulus the number of sets and the training load are the main acute programme variables that are altered. Classical strength/power periodization models may extend over sixteen to twenty weeks and are often divided into three active cycles, a taper period and a recovery cycle (Plisk and Stone 2003) (Figure 2.1). During the first cycle the primary goal is to increase muscle cross sectional area. To achieve this adaptation rest periods are set to short intervals with exercise selection and order chosen to ensure different muscle groups experience adequate stress then recovery (Plisk and Stone 2003). The second cycle of the training period comprises the main strength phase with exercise selection focused on movements that produce the largest forces (Turner 2011). Additionally, duration of rest periods are

increased to maintain high force outputs and exercise order frequently arranged so that different muscle groups produce maximum force in the same session (Kramer and Fleck 2004). The third and final active cycle of the model focuses on the development of muscular power. Repetition velocity and exercise selection are generally perceived to be the two most important acute programme variables to stimulate the required adaptations in this cycle (Kramer and Fleck 2004).

**Figure 2.1:** Schematic overview of classical strength/power periodization model, illustrating changes in volume, intensity and amount of technical practice across the different phases



Adapted from: Plisk, S.S. Stone, M.H. (2003). *Periodization Strategies. Strength and Conditioning Journal. 25(6): pg 24.*

The acute variable model is currently promoted by the National Strength and Conditioning Association (Baechle and Earle 2008) and the American College of Sports Medicine (American College of Sports Medicine 2009). Both organisations have created a framework where training is perceived as the development of fitness components and constraints are applied to the acute variable model to assist the design of appropriate training sessions. Table 2.1 illustrates recommended values for the acute variables when attempting to

develop fitness components associated with resistance training. This approach has been criticised when the primary goal is to enhance sports performance (Siff 2003). The main concern is that fitness components are considered too broad and do not take into account different characteristics of the force-time and force-load relationships which some consider important for determining success in sport (Siff 2003). This concern is supported by contemporary paradigms in strength and conditioning which promote the importance of concepts such as rate of force development (RFD), speed-strength and strength-speed for athletes (Stone, Stone and Sands 2007, Tan 1999). However, the variable model and associated guidelines provide an empirical basis on which to design appropriate resistance training programmes, with research consistently expanding the evidence base.

**Table 2.1:** Acute variable guidelines

| <b>Training Goal</b>         | <b>Load (%1RM)</b> | <b>Goal Repetitions</b> | <b>Number of Sets</b> | <b>Rest Period Length</b> |
|------------------------------|--------------------|-------------------------|-----------------------|---------------------------|
| <b>Strength</b>              | ≥ 85               | ≤ 6                     | 2 – 6                 | 2 – 5 minutes             |
| <b>Power single-effort</b>   | 80 – 90            | 1 – 2                   | 3 – 5                 | 2 – 5 minutes             |
| <b>Power multiple-effort</b> | 75 – 85            | 3 – 5                   | 3 – 5                 | 2 – 5 minutes             |
| <b>Hypertrophy</b>           | 67 – 85            | 6 – 12                  | 3 – 6                 | 30 seconds – 1.5 minutes  |
| <b>Muscular endurance</b>    | ≤ 67               | ≥ 12                    | 2 – 3                 | ≤ 30 seconds              |

Adapted from: Baechle, T.R. Earle, R.W. (2008). *Essentials of strength training and conditioning*. Human Kinetics, Champaign, Il. pg 401.

Alternative resistance training models are primarily used to design training programmes aimed at improving sports performance. One of the most prominent is the means and methods model which was conceptualised by Eastern European researchers and has subsequently been presented in a number of English texts (Siff 2003, Verkhoshansky 1986, Issurin 2008, Verkhoshansky 2006, Bondarchuk 2007). Variability exists between the different translations in key definitions used to define and delimit factors of the model. This variability may be due to different interpretations of language and/or concepts. It is, however, consistently remarked that the means and methods model is used to create acute mechanical and physiological stimuli, whose effects are accrued over time to induce adaptations that enhance performance in a specific sport (Issurin 2008, Verkhoshansky 2006). In the simplest form of the model, the means refer to exercises or technical drills and the methods include generalised structures which determine how the exercises are performed (Siff 2003). Frequently, the means are categorised based on the relatedness of

the kinematics and kinetics of the training exercise and the movements performed within the sport. A common classification scheme organises each exercise or training drill into one of three categories: general, general-specific, and specific (Bondarchuk 2007, Baker 1996). General means are classified as exercises and drills which are unlikely to directly enhance proficiency in a sports movement, but rather serve to develop fitness variables associated with performance (Baker 1996, Smith 2005). General-specific means include exercises and drills which exhibit a higher degree of mechanical specificity with the sporting movement and can potentially enhance performance through both direct and indirect processes (Smith 2005). Specific means exhibit kinematic and kinetic profiles that closely match the sporting movements and are expected to have a direct effect on movement proficiency (Baker 1996). Table 2.2 provides examples of general, general-specific, and specific exercises for a range of athletes.

**Table 2.2:** Example means classification for various athletes

| <b>Athlete</b>                     | <b>general</b>   | <b>general-specific</b>  | <b>specific</b>   |
|------------------------------------|--|--|---|
| <b>American Football (linemen)</b> | Olympic lifts, powerlifting lifts, + most exercises performed with barbells, dumbbells, kettlebells etc  | pushing a weighted implement (e.g. sled, tire, special training apparatus, etc), performing intermittent hitting drills  | one on one contests against an opponent for 4-10 second repetitions |
| <b>Track and Field (100m)</b>      | Olympic lifts, powerlifting lifts, + most exercises performed with barbells, dumbbells, kettlebells etc  | double/single leg bounds, jumps, landings, depth jumps, alternating bounds, sprints wearing a weighted belt or vest, sprints performed on mild gradients   | variable intensity sprints over different distances                 |
| <b>Track and Field (High Jump)</b> | Olympic lifts, powerlifting lifts, + most exercises performed with barbells, dumbbells, kettlebells etc  | any bounds, jumps, weighted jumps, depth jumps, etc other than the competition exercise  | high jumps over various heights                                     |
| <b>Olympic Weightlifter</b>        | rows with barbells, dumbbells, kettlebells, presses/swings with dumbbells, kettlebells, GHR, pull ups, back raises, step ups, lunges, jumps onto a box, bounds, landings, depth jumps, etc | front squat, back squat, overhead squat, box squat, SS Bar squat, cambered bar military press, overhead press off of pins/out of chains, jerk from stands, power jerk (if split jerk is used in competition), split jerk (if power jerk is used in competition), clean from blocks, clean from hang, power clean, snatch from blocks | Snatch and clean & jerk with varied intensities                     |

In contrast to the approach of classifying means based on their mechanical similarity with competitive sports movements, Siff (2003) recommended that means should be conceptualised on the basis of the afferent signals they transmit to the nervous system. Using this approach, Siff (2003) outlined four categories of means:

- 1) Stimulation when muscular tension is produced by voluntary effort against external resistance, and the resistance of the moving load accelerates and regulates the effector impulses to the muscles
- 2) Stimulation by the kinetic energy of a falling object or body, when the effort is primarily reflexive
- 3) Stimulation caused primarily by voluntary effort, under conditions where additional external mechanical stimulation is absent or limited
- 4) Stimulation of muscle elicited or intensified involuntary by means of external electric current

The majority of resistance exercises performed in contemporary training of athletes are described by the first categorisation. However, Siff (2003) states that these exercises can be further divided into two groups. The first group comprise exercises where maximum force is developed after appreciable preliminary muscular tension. Examples include the squat and bench press where peak force in the concentric phase is preceded by large forces to decelerate the system load during the eccentric phase of the movement (Elliott, Wilson and Kerr 1989, McLaughlin, Lardner and Dillman 1978). The second group of exercises include actions where maximum force is developed without appreciable preliminary muscular tension. Examples include the deadlift and clean where only a low level of force is required in the preparatory phase to hold the body in equilibrium (Souza, Shimada and Koontz 2002, Brown and Abani 1985). It is proposed that this delineation is important as only the second group of exercises is considered to have the potential to increase the rate at which muscles can transition from rest to an active state (Siff 2003). In strength and conditioning literature this feature is often defined as starting strength and is proposed to be important in determining performance in very short duration high force activities such as sprinting (Tidow 1990). However, research on neuromuscular parameters such as starting strength is limited and at present largely speculative and anecdotal.

The second category of means described by Siff (2003) includes exercises such as depth jumps and bench throws. In both exercises, the kinetic energy of the falling object can be partly transformed into elastic energy to augment the subsequent concentric work (Siff 2003). In addition, rapid stretch-shortening cycle (SSC) actions are likely to induce reflex mechanisms that can also contribute to performance (Komi 2000). A growing body of research suggests that these types of plyometric exercises may increase performance and reduce injury risk through adaptations which are distinct from those stimulated by standard resistance exercises (Siff 2003, Hubscher et al. 2010, Risberg et al. 2007, Vissing et al. 2008).

The third category of means described by Siff (2003) comprises primarily isometric actions. Initial research studies investigating the effects of isometric training concentrated primarily on changes in maximum strength (Wilson and Murphy 1996). More recently, isometric training has been used to investigate potential changes in stiffness of the tendon-aponeurosis complex. (Kubo et al. 2006). A number of studies have demonstrated that isometric training can significantly increase stiffness of soft tissues, with changes influenced by factors such as the joint angle used in training (Kubo et al. 2006, Kubo et al. 2006, Kubo et al. 2009). In addition, research also suggests that isometric actions may be more effective than dynamic actions in creating soft tissue adaptations (Kubo et al. 2009). At present it is not clear if stiffer tendon-aponeurosis complexes are advantageous for sporting performance. It is hypothesised that stiffer complexes transmit forces to the limb at a faster rate and store more elastic energy for a given amount of joint displacement (Siff 2003). However, data from cross sectional studies have been mixed with both positive (Bojsen-Moller et al. 2005) and negative (Kubo et al. 2000) correlations between stiffness and performance reported. Thus, further research is required to determine the effects and importance of soft tissue adaptations.

The final category of means outlined by Siff (2003) comprises the practice of electromyostimulation (EMS). Initially, EMS methods were confined to single electrodes attached to defined muscle groups. With technical developments EMS has now progressed from local stimulation to a whole-body training method where multiple groups of muscles and kinematic chains can be stimulated simultaneously (Babault et al. 2007). In a recent systematic review of EMS training with experienced and elite athletes, the data highlighted that strength, power, RFD, vertical jump and sprinting performance could be positively affected (Filipovic et al. 2012). The authors concluded that the best results are achieved by

athletes if they combined EMS protocols with either dynamic or isometric training depending on the desired adaptations (Filipovic et al. 2012).

The categorisation of means outlined by Siff (2003) places more emphasis on the underlying mechanical and neurophysiological processes associated with each type of exercise rather than focusing on their gross kinematics and kinetics. The advantage of this approach is that it highlights additional features of exercises that research suggests can influence adaptations, but perhaps would not be apparent from a basic overview of the movement itself. However, Siff (2003) concludes that whilst these different categories of means can provide unique stimuli, coaches and athletes should also select exercises that exhibit close mechanical relationships with the sporting movements to ensure maximum transfer of adaptations. Despite results from individual studies supporting some of the hypotheses presented by Siff (2003) and his categorisation of training means, there has not been the same systematic approach to research that has been conducted with the acute variable model. As a result, the validity of the approach is at present unknown.

Once appropriate means have been selected, the acute training stimulus is determined by performing a particular method. However, variations also exist for this component of the model (Siff 2003, Verkhoshansky 1986, Issurin 2008, Verkhoshansky 2006). Issurin (2008) stated that methods could be classified using three methodological principles and subdivided into five major groups (Table 2.3). The methodological principles outlined by Issurin (2008) encompass a general perspective to exercise and as a result provide limited assistance when developing resistance training programmes for athletes. In contrast, Verkhoshansky (2006) described a more detailed list of methods specific to resistance training (Table 2.4). Each of the methods discussed reflects current practical recommendations and contemporary research in the field of strength and conditioning. The repeat method outlined by Verkhoshansky (2006) regulates the number of repetitions performed in a set based on the athlete's ability to maintain high kinetic outputs and appropriate technique. This method is currently recommended by most sources for the development of muscular power. Practical guidelines frequently state that six successive repetitions is the maximum number that should be performed in a single set as fatigue accrued diminishes the quality of further repetitions and hence attenuate the adaptive response (American College of Sports Medicine 2009, Baechle and Earle 2008). However, research to support the notion that six repetitions are indicative of a general performance threshold is limited. The majority of biomechanical studies that have investigated the

kinetics of resistance exercises have been restricted to single repetitions, with only a small number of studies assessing performance over a complete set. Eastern European researchers investigated the kinematics and kinetics of high-level Olympic weightlifters performing the snatch exercise over multiple repetitions with an 80% 1RM load (Lukashev, Medvedev and Melkonian 1979). The results demonstrated that kinetics were relatively stable within the range of eight to ten repetitions, whereas significant differences in kinematics were found after seven repetitions. It is unclear whether similar results would be obtained with general athletes who exhibit less proficiency in the weightlifting movements. Baker and Newton (2007) demonstrated that elite rugby league players could maintain high power outputs during the jump squat for approximately five repetitions. The research was limited by the use of a single absolute load for all participants. This limitation was overcome by Thomasson and Comfort (2012) who investigated squat jump kinematics and kinetics across a range of loads with high-level athletes performing a maximum of six repetitions in a set. The results illustrated that load influenced the maintenance of power with significant decreases noted during the sixth repetition of the heaviest load condition (60% 1RM). Importantly, the results also demonstrated that when using light loads (0 to 40% 1RM) four to six repetitions are required to reach maximum power values.

**Table 2.3:** Methodological principles and characteristics of training methods

| Methodological principle | Work-rest conditions  | Training Method  |
|--------------------------|---|--|
| Continuous exercise      | Uniform performance   | Continuous uniform method  |
|                          | Non-uniform performance (includes periodic accelerations)   | Continuous alternating method<br>Fartlek                                     |
| Intermittent exercise    | Work-rest ratio is strictly prescribed, rest interval is predetermined                                | Interval method (long-interval, medium-interval, and short-interval methods) |
|                          | Work-duration is predetermined, rest interval is not strictly prescribed and allows complete recovery | Repetition method  |
| Game exercise            | According to the game scenario  | Game method  |

Adapted from: Issurin, V. (2008). Principles and basics of advanced athletic training. Ultimate Athlete Concepts, Michigan, USA. pg 11.

The serial and complex methods outlined by Verkhoshansky (2006) have also attracted the focus of researchers in strength and conditioning. The serial method can be considered as an extension of the repeat method where the aim is to increase the overall quality of a given number of repetitions. In contemporary research the serial method is referred to as cluster sets and consists of a series of single repetitions interspersed with ten to thirty seconds rest to create an extended set (Haff et al. 2008). Cross-sectional research has established that cluster sets can increase accumulated values for velocity and power in comparison to the traditional method of performing repetitions continuously (Lawton, Cronin and Lindsell 2006, Haff et al. 2003). Results from longitudinal studies have been more varied with some evidence to show that cluster training can lead to greater improvements in velocity and power (Lawton, Cronin and Lindsell 2004), and other studies either reporting no differences (Hansen et al. 2011b) or greater results for the performance of continuous repetitions (Rooney, Herbert and Balnave 1994). Further research incorporating exercises that are considered most compatible with the serial method (e.g. clean, snatch, jump squat) is required to establish potential utility for elite athletes.

The complex method outlined by Verkhoshansky (2006) has received considerable research attention over the last fifteen years (Sale 2002). The goal of the complex method is to enhance performance during explosive movements (e.g. vertical jump or sprint) by first performing a heavy resistance exercise (e.g. maximum squat). The preceding contractile activity from the heavy resistance can produce both fatigue and a postactivation potentiation effect (PAP), with the balance determining if performance is positively or negatively affected (Sale 2002). Numerous acute studies have clearly demonstrated that performance can be enhanced with the complex method (Baker 2003, Young, Jenner and Griffiths 1998, Hrysomallis and Kidgell 2001, Mitchell and Sale 2011); however, many studies have also failed to show positive results (Duthie, Young and Aitken 2002, Scott and Docherty 2004), indicating that it may be difficult to create a favourable balance between fatigue and PAP for all individuals. Longitudinal research investigating chronic adaptations from the complex method have generally been positive with some studies demonstrating superior results compared with traditional methods (Adams, O'Shea and O'Shea 1992, Verkhoshansky and Tatyana 1973) and others reporting improvements of a similar magnitude (MacDonald, Lamont and Garner 2012, Lyttle, Wilson and Ostrowski 1996). Importantly, longitudinal studies have failed to incorporate designs that assess whether the training protocols are consistently eliciting a PAP effect for each participant. Such a design would be challenging and illustrates the difficulty in applying the approach in many practical settings where the

balance between fatigue and PAP is required for multiple athletes that may exhibit substantial variability with the phenomenon.

**Table 2.4:** Methodological principles and characteristics of training methods

| Method           | Description   |
|------------------|---|
| Repeat Method    | Used to develop primarily speed or power. Repetitions are performed until form deteriorate or velocity/power drops below desired values                               |
| Interval Method  | Multiple sets are performed which comprise a large number of repetitions with short rest durations between sets   |
| Serial Method    | Multiple sets are performed to produce a series; multiple series are then performed for each exercise. The rest period between sets and series is generally different |
| Failure Method   | Sets are performed until no more repetitions can be completed due to fatigue  |
| Circuit Training | Variant of the interval method where a single set consists of performing multiple exercises in sequence   |
| Contrast Method  | High velocity repetitions are performed assisted and then with light resistance (or vice versa)   |
| Complex Method   | Light load high velocity sets are performed after sets of high load low velocity repetitions  |

Adapted from: Verkhoshansky, Y.V. (2006). *Special strength training: A practical manual for coaches*. Ultimate Athlete Concepts, Michigan, USA. pgs 6-8.

In summary, resistance training models are designed to assist practitioners in developing effective training programmes, and to facilitate systematic research that can be used to form an evidence base. A key feature of these models is to constrain the possible configurations and create programmes that stimulate specific adaptations. This process, however, only

constrains and still leaves the programmer with an element of creativity. Two of the most popular training models for developing resistance training programmes are the acute variable model and the means and methods model. The advantage of the former is the extensive research base and subsequent guidelines that have been developed. However, it has been argued that the acute variable models focus on developing aspects of fitness is limited in terms of enhancing sports performance. Instead the means and methods model, which was designed for the purpose of improving sports performance, is recommended. Currently, this latter model is not supported by a systematic evidence base. In addition, diverse interpretations of the model from its conception in Eastern Europe have limited its progress. Further development of the model should seek to standardise structure and nomenclature prior to conducting original research.

### **2.1.3 Resistance training and sports performance**

In contrast to recent acknowledgements of potential health benefits associated with resistance training, the view that the training modality can be used to improve sports performance has a much longer history. The extent to which training with dumbbells and barbells could increase strength and functional capacity became clear at the beginning of the twentieth century when organised competitive weightlifting sports were created (Fry and Newton 2002). Bodybuilders were the first group of athletes to promote resistance training to the general public through popular media. However, the extreme muscular hypertrophy exhibited by bodybuilders caused many to suggest the training would create athletes that were too big and slow. The sport of weightlifting, which was permanently included in the Olympic Games in 1904, demonstrated the functional strength, power and athleticism that could be developed from the training. Track and field throwers were the first non-strength athletes to adopt resistance training as a means of improving sports performance in the 1950s (Fry and Newton 2002). In the late 1960s American football players began to incorporate resistance training as part of their overall physical preparation (Fry and Newton 2002, Todd 1994). Importantly, college and professional teams began to employ strength coaches which greatly expanded the use of resistance training in sports. This progress has culminated in virtually all athletes ranging from wrestlers to distance runners now incorporating resistance training as part of the overall regime.

Despite the now wide spread use of resistance training with athletes it remains difficult to assess the impact of the training on performance. It is likely that the influence of resistance will vary between sports, positions (i.e. different roles in team sports) and between

individuals who vary in physical, technical and tactical abilities. From a research perspective, quantifying the impact of resistance training on sports performance is difficult as performance in sport can be considered a complex multifactorial construct rather than a variable that can be directly measured (Atkinson 2000, Currell and Jeukendrup 2008). In team sports where resistance training is considered to play a pivotal role in the athletes' overall preparation, it is unclear what factors determine a given level of performance (Atkinson 2000, Currell and Jeukendrup 2008). As a result, assessing the importance of resistance training in team sports remains an unresolved issue. Performances in individual sports, where time or distance are the dominant factors, provide more appropriate models to assess the effects of resistance training. In addition, performance proxies such as maximum effort time trials may provide a more suitable testing environment for events where competition performance may be significantly influenced by external factors such as ambient conditions and tactics of opponents. The following sections provide an overview of resistance training and the most widely researched individual sports, which include sprinting, distance running and cycling.

Sprinting has previously been described as a multidimensional skill that includes an acceleration phase, a transition phase and a maximum velocity phase (Delecluse 1997). Faster speeds are achieved by a combination of increased stride length and stride frequency. Increases in stride length are achieved by exerting greater support forces during ground contact, whereas increases in stride frequency are obtained primarily from the fast and coordinated actions of the hip musculature (Dorn, Schahe and Pandy 2012). Using a regression approach, Weyand et al. (2000) demonstrated with a heterogeneous group of athletes that faster top speeds were best explained by greater ground reaction forces expressed relative to bodyweight. This result provides a clear mechanism to explain how resistance training could be used to improve performance. Additionally, Weyand et al. (2000) reported that during level sprinting foot contact times at maximum speed were approximately 0.11 s. This duration is considerably shorter than the time required for skeletal muscles to produce maximum force ( $\approx 0.6$  s (Viitasalo and Komi 1978)); therefore resistance training programmes aimed at improving sprinting are suggested to include stimuli that would improve variables such as RFD (Siff 2003). Numerous longitudinal studies have demonstrated that moderate length resistance training programmes can improve aspects of sprint performance. Blazeovich and Jenkins (2002) reported that both high- and low-velocity resistance training could be used to improve the strength and twenty metre acceleration time of elite male junior sprinters over a seven week cycle. However, no control group was included and the athletes maintained their sprint training throughout the period

making it difficult to assess the overall impact of the resistance training. The majority of studies that have investigated the effects of resistance training on aspects of sprinting have recruited relatively untrained participants or athletes competing in team sports (Table 2.5). Of the nineteen studies reviewed that included both strength and performance measures, eighteen reported increases in strength and thirteen reported significant increases in measures associated with sprinting performance. Collectively, the results show that transfer of increased strength is limited, and large increases in force production capabilities are required to create much smaller improvements in sprinting performance. Results from multiple studies suggested that the transfer of training may be better improved if heavy resistance training is combined with plyometrics or explosive resistance exercises (Lyttle, Wilson and Ostrowski 1996, Kotzamandis et al. 2005, Ross et al. 2009). More longitudinal studies are required with elite level athletes conducted over longer time periods (i.e. one year vs. typical eight to twelve weeks) to portray a more relevant picture of the effectiveness of resistance training to improve sprint performance.

**Table 2.5:** Summary of previous studies investigating the effects of strength training on sprinting performance

| Authors                      | Participants  | Intervention  | Outcome measures   | % Change in performance  |
|------------------------------|---|---|--|--|
| Blazevich and Jenkins (2002) | Nationally ranked male junior sprinters (n=10) age 19.0±1.4 yr.                                 | 7wk, 4wk of standard training comprising two resistance training sessions per wk (squats, hip extension, leg curl, leg extension) in addition to sprint training. After 4wk, participants were split into high velocity (30-50% 1RM) and low velocity group (70-90% 1RM)  | 1RM squat,<br><br>Isokinetic hip extension<br><br>20 m acceleration performance<br><br>Flying 20 m performance | *High velocity = 12.4%<br>*Low velocity = 11.8%<br><br>*High velocity = 15.6%<br>*Low velocity = 15.4%<br><br>*High velocity = 4.3%<br>*Low velocity = 2.9%<br><br>High velocity = 1.9%<br>Low velocity = 2.4% |
| Chelly et al. (2009)         | Junior soccer players (n=22) 17.0±0.4 yr.   | 8 wk intervention, training 2 days per wk. Resistance training group performed heavy back squats, and a control group   | 1RM half squat<br><br>5 m sprint performance<br><br>Maximum sprint velocity                                    | *Resistance = 28.6%<br>Control = 3.7%<br><br>*Resistance = 7.1%<br>Control = 0.6%<br><br>*Resistance = 11.9%<br>Control = 4.2%   |
| Coutts et al. (2004)         | Youth male rugby league players (n=42) age 16.7±1.1 yr.   | Supervised and Unsupervised groups. Same 12 wk program given, 3 days per wk, linear periodized program  | 3RM squat<br><br>10 m sprint performance<br><br>20 m sprint performance  | *Supervised = 40.1%<br>*Unsupervised = 25.5%<br><br>*Supervised = 1.2%<br>*Unsupervised = 1.1%<br><br>*Supervised = 1.2%<br>*Unsupervised = 0.8%   |
| Deane et al. (2005)          | Recreationally trained male and female weight trainers (n=24 male and n=24 female) 22.2±1.4 yr. | 8wk intervention, treatment and control. Training: 3 days per wk, elastic tubing hip flexor exercise.   | Isometric hip flexor torque<br><br>10-yard dash performance<br><br>40-yard dash performance                    | *Treatment = 11.4%<br>Control = -6.6%<br><br>*Treatment = 11.4%<br>Control = -3.7%<br><br>*Treatment = 4.4%<br>Control = -0.4%   |
| Delecluse et al. (1995)      | Untrained college aged males (n=78) 20.4±1.6 yr.  | 7wk intervention, high resistance, high velocity and two control groups (running only and passive). Training: 3 days per wk (2 specific training, 1 sprint training). High resistance followed periodized program including standard upper and lower body exercises. High velocity group performed unloaded plyometric exercises. | 100 m performance<br><br>10 m acceleration   | Heavy resistance = 0.2%<br>*High Velocity = 1.7%<br>Run Control = -0.7%<br>Passive Control = -0.3%<br><br>Heavy resistance = 1.1%<br>*High Velocity = 7.1%<br>Run Control = -1.2%<br>Passive Control = -3.6%   |

|                           |   |  |   |  |
|---------------------------|---|--|---|--|
| Fry et al.(1991)          | Division I female volleyball players (n=14)<br>19.6±0.6 yr.                 | 12 wk intervention, comprising resistance training and plyometric drills. Strength training comprised whole body workouts in a periodized program.   | 1RM squat<br>10-yard dash performance<br>40-yard dash performance | *20.5%<br>8.2%<br>0.9%   |
| Harris et al. (2000)      | Trained male athletes (n=42)<br>19.0±1.8 yr.                                | 13 wk intervention, preparatory phase of 4 wks, then participants split into 3 groups for 9 wks: High force, High power and combination. Training 4 days per wk. High training group used loads of 80-85% 1RM, High power used loads of 30% maximum force. Combination group performed both types of training. | 1RM squat<br>30 m performance                                     | *High force = 9%<br>High power = 3.5%<br>*Combined = 10%<br><br>High force =0.1%<br>High power = -0.7%<br>Combined =1.4% |
| Harris et al. (2008)      | Elite rugby league players (n=18)<br>21.8±4.0 yr.                           | 4 wk familiarisation period, then 6 wk intervention, training 6 days per wk. Two groups, both performing squat jumps, one group with 80% 1RM, and the other the load that maximised their power output.  | 1RM Squat<br>10 m sprint performance<br>30 m sprint performance   | *Strength = 16.6%<br>*Power = 9.2%<br><br>*Strength = 2.7%<br>*Power = 1.6%<br><br>*Strength = 1.7%<br>*Power = 1.3%     |
| Hoffman et al. (2004)     | Division III male American football players (n=20)<br>19.1±1.3 yr.          | 15 week intervention, training 4 days per wk. Participants splint into a powerlifting group performing periodized program including traditional resistance exercises, and a Olympic weightlifting group performing similar exercise with addition of Olympic weightlifting movements.                          | 1RM squat<br>40-yard dash performance                             | *Powerlifting = 11.5%<br>*Olympic = 12.6%<br><br>Powerlifting = 0.8%<br>Olympic = 1.4%                                   |
| Kotzamandis et al. (2005) | Soccer players and age matched recreational controls (n=32)<br>17.4±0.8 yr. | 13 wk intervention, training 3 days per wk. Soccer players were split into two groups: heavy resistance training and a combined group performing resistance training and speed sessions. Both training programs were periodized.   | 1RM half squat<br>30 m performance                                | *Strength = 10.0%<br>*Combined = 8.7%<br>Control = 1.5%<br><br>Strength = 0.4%<br>*Combined = 3.3%<br>Control = 0.3%%    |

|                          |   |   |   |   |
|--------------------------|---|---|---|---|
| Lyttle et al. (1996)     | Male recreational athletes with no resistance training experience (n=39) 23.5±2.4 yr. | 8 wk intervention, training 2 days per wk. Maximum power group performing squat jumps and bench press throw, combined group performing lower body maximum strength and plyometric drills.   | 1RM squat<br><br>40 m performance<br><br>Flying 20 m performance                                | *Power = 14.7%<br>*Combined = 14.8%<br><br>Power = 1.7%<br>Combined = 0.8%<br><br>Power = 0.4%<br>Combined = 1.3%   |
| McBride et al. (2002)    | Recreationally trained males with resistance training experience. (n=26) 23.2±1.5 yr. | 8 wk intervention, training 2 days per wk. Maximum strength group performing jump squats with 80% 1RM, maximum power group performing jump squats with 30% 1RM and a control group.   | 1RM squat<br><br>5 m performance<br><br>10 m performance<br><br>20 m performance                | *Strength = 8.6%<br>*Power = 10.9%<br>Control = 6%<br><br>*Strength = -6.8%<br>Power = 0.8%<br>Control = -3.7%<br><br>Strength = -4.4%<br>Power = 2.2%<br>Control = -1.1%<br><br>Strength = -1.8%<br>Power = 1.6%<br>Control = 1.0%       |
| Murphy and Wilson (1997) | Recreationally trained males with resistance training experience. (n=27) 22.0±4.0 yr. | 8 wk intervention, training 2 days per wk. Heavy resistance group and a control group. The resistance group performed a periodized program using the squat.   | 1RM squat<br><br>40 m sprint performance  | *Strength = 20.9%<br>Control = 4.0%<br><br>*Strength = 2.3%<br>Control = 1.0%   |
| Rønnestad et al. (2008)  | Professional male soccer players (n=21) 22.5±2.3 yr.                                  | 8 wk intervention, training 2 days per wk. Moderate load resistance training comprising the squat and hip flexion exercise, combined group performing resistance and plyometric training, and control group.  | 1RM Squat<br><br>10 m sprint performance<br><br>Flying 10 m performance<br><br>40 m performance | *Pooled strength and combined = 25%<br>Control = 4%<br><br>*Pooled strength and combined = 1.7%<br>Control = 0%<br><br>*Pooled strength and combined = 0.8%<br>Control = 0%<br><br>*Pooled strength and combined = 1.1%<br>Control = 0.8% |
| Ross et al. (2009)       | Non-elite male athletes with experience in resistance training. (n=25) 19.8±1.5 yr    | 8 wk intervention, training 4 days per wk. Resistance group, spring group and combined group. Resistance training was periodized and included upper and lower body traditional resistance exercises. Sprint training included resisted and non-resisted sprints | 1RM squat<br><br>20 m sprint performance<br><br>30 m sprint performance                         | *Resistance = 4.5%<br>*Sprint = 5.5%<br>*Combined = 5.3%<br><br>*Resistance = 1.6%<br>*Sprint = 5.0%<br>*Combined = 8.0%<br><br>Resistance = 0.6%<br>Sprint = 1.6%<br>*Combined = 2.3%  |

|                                  |   |   |  |  |
|----------------------------------|---|---|--|--|
| Saez de Villarreal et al. (2012) | Male recreational athletes with no resistance training experience (n=60) 20.4±2.1 yr  | 8 wk intervention, training 3 days per wk. Five groups were created including: 1) combined training, 2) heavy-resistance, 3) Power resistance training 4) Ballistic resistance exercise, 5) plyometric  | 1RM squat<br><br>30m sprint performance                        | *Combined = 20.3%<br>*Heavy resistance = 11.1%<br>*Power resistance = 17.9%<br>*Ballistic resistance =14.3%<br>*Plyometric = 6.8%<br><br>Combined = 0.23%<br>Heavy resistance = 0.13%<br>Power resistance = 0.33%<br>Ballistic resistance =0.68%<br>Plyometric = 0.91% |
| Tricoli et al. (2005)            | Recreationally trained males with resistance training experience. (n=32) 22.0±1.5 yr. | 8 wk intervention, training 3 days per wk. Olympic weightlifting group performing high pulls, cleans and jerks. Vertical jump group performing vertical and horizontal plyometric drills, and a control group.  | 1RM half squat<br><br>10 m performance<br><br>30 m performance | *Weightlifting = 43.7%<br>*Plyometric = 47.8%<br>Control = 6.4%<br><br>*Weightlifting = 3.7%<br>Plyometric = 2.7%<br>Control = 0.6%<br><br>Weightlifting = 0.1%<br>Plyometric = 0.8%<br>Control = -0.6%  |
| Wilson et al. (1996)             | Recreationally trained males with resistance training experience. (n=27) 23.8±4.8 yr. | 8 wk intervention, training 2 days per wk. Strength training group performing the squat and bench press with progressive increases in load, and a control group.  | 1RM Squat<br><br>40 m performance                              | *Strength = 20.9%<br>Control = 4.0%<br><br>*Strength = 2.3%<br>Control =0.0%   |
| Wilson et al. (1993)             | Recreationally trained males with resistance training experience. (n=55) 23.6±5.3 yr. | 10 wk intervention, training 2 days per wk. Four groups (3 experimental and 1 control). Two experimental groups performed 6 to 10 reps in the squat. The Strength training group performed the exercise with a heavy load, whereas the power group performed the exercise with a 30% 1RM load. The third experimental group performed drop jumps. | Isometric Squat<br><br>30 m performance                        | *Strength = 14.4%<br>Power = 2.0%<br>Plyometric = 0.7%<br>Control = -2.7%<br><br>Strength = 0.2%<br>*Power = 1.1%<br>Plyometric = 0.2%<br>Control = -0.8%  |

\*Significant difference between pre and post measures ( $p < 0.05$ )

The case for resistance training improving performance in distance running is less obvious than that for sprinting. Distance runners were initially hesitant to perform resistance exercises due to concerns that muscle hypertrophy may reduce capillary density and mitochondrial function, thus reducing aerobic capacity (Yamamoto et al. 2008). In addition, no clear mechanisms to explain how resistance training could improve endurance performance were originally proposed. Standard performance models of endurance running predict that three physiological variables ( $\dot{V}O_2\text{max}$ , %  $\dot{V}O_2\text{max}$  at lactate threshold and running economy) combine to determine average running speed (Bassett and Howley 2000). Initial studies conducted to investigate the potential for resistance training to improve running performance demonstrated that the training had no effect on  $\dot{V}O_2\text{max}$  (Hickson et al. 1988, Hennessy and Watson 1994, Johnston et al. 1997) or lactate threshold values (Hickson et al. 1988, Paavolainen et al. 1999) in trained individuals. A plausible means to explain how resistance training could improve endurance performance of well trained athletes was first identified by Johnston et al. (1997). The authors focused on the effect of resistance training on running economy, hypothesising that increased strength could lead to improved efficiency. Johnston et al. (1997) conducted their intervention study with twelve non-elite female distance runners. Each athlete performed similar endurance training sessions over a period of ten weeks, with six participants randomly allocated to the intervention condition, which included an additional three resistance training sessions per week. The resistance training sessions comprised fourteen standard resistance exercises split into two groups and performed on alternating sessions. Repetitions ranged from 6RM to 20RM with progressive increases in load as the athletes increased their strength. Following the ten week training period the intervention group increased their upper and lower body strength by 24.4 and 33.8%, respectively. The control group exhibited no increases in strength over the training period. Changes in running economy were restricted to the intervention group where a significant increase of 4% on average was obtained. Based on the study design, Johnston et al. (1997) were unable to explain the mechanisms by which resistance training improved running economy. The authors speculated that improvements may have been caused by a number of mechanisms including shifts in ATPase activity of individual muscle fibres, changes in running mechanics, and changes to motor unit recruitment patterns.

Another influential study in the area of resistance training and endurance performance was conducted by Paavolainen et al. (1999). The authors recruited twenty two elite male cross country runners and used stratified sampling to allocate participants to the intervention or control group based on their aerobic performance. The experimental training period was

conducted over nine weeks and was performed following the competitive season. Those allocated to the control group performed standard endurance sessions and circuit training. Those allocated to the intervention group replaced approximately 30% of the standard endurance training volume with resistance training. The resistance training sessions were designed in attempts to equate the total training volume; however, the authors did not explain the methods used to calculate or equate volumes for each training mode. In contrast to the resistance training protocols used by Johnston et al. (1997), Paavolainen and colleagues (1999) used only explosive lower-body resistance exercises with light loads performed at maximum velocity. This type of training was used in an effort to prioritise neuromuscular adaptations rather than gross changes to the skeletal musculature. At the end of the training intervention, slight decreases in strength were measured for the control group, whilst significant increases were obtained for those performing resistance training. In accordance with the classical model of endurance performance, Paavolainen et al. (1999) assessed changes in  $\dot{V}O_2\text{max}$ , lactate threshold and running economy. The researchers found that the inclusion of resistance training failed to improve  $\dot{V}O_2\text{max}$  and lactate threshold, but did improve running economy by 8.1%. Five kilometre running time was also assessed as a performance related measure. Only those allocated to the experimental condition demonstrated improvements in performance, with a significant correlation obtained with the pooled data for improvements in 5 km time and running economy ( $r = 0.54, p < 0.05$ ).

More recently, research investigating the effects of resistance training on endurance performance has distinguished between short-duration endurance capacity (<15 min) and long-duration endurance capacity (>30 min) (Aagaard and Andersen 2010). For both categories, evidence is now available to demonstrate that performance of well-trained and top-level endurance athletes can be improved when heavy resistance training is incorporated within the training regime (Storen et al. 2008, Mikkola et al. 2007b, Mikkola et al. 2007a). This is despite cellular studies revealing that resistance and endurance training create distinct and cross inhibitory signalling events involving the Akt/mTOR and AMPK pathways, respectively (Atherton et al. 2005, Baar 2006). At present it is still not fully understood which adaptive mechanisms improve performance, however, it is believed that the mechanisms responsible are distinct for short-term and long-term endurance performances (Coffey and Hawley 2007). In a recent review of potential mechanisms, Aagaard and Andersen (2010) concluded that future research to resolve the issue should investigate changes in the percentage of type IIA muscle fibres and increased RFD as the most likely candidates to explain increases in running economy and performance.

Similar to over-ground running, the sport of cycling is traditionally separated into sprint and endurance events (Foley, Bird and White 1989). Studies comparing the anthropometric and physical qualities of the two groups have reported that sprint cyclists are generally shorter and heavier, with larger muscular girths and greater strength levels than endurance cyclists (Foley, Bird and White 1989, McLean and Parker 1989). Additionally, correlation research conducted with sprint cyclists from local-level to international-calibre revealed that strength and power were strongly correlated with performance related measures, with RFD exhibiting low to moderate correlation values (Stone et al. 2004). Based on the results from these studies it would be expected that resistance training would be most effective in the performance enhancement of sprint cyclists. However, longitudinal research has focused on the potential for resistance training to improve performance of endurance cyclists. This apparent inconsistency reflects the extensive research base that has investigated concurrent strength and endurance training, with cycling providing a contrasting low impact, high volume model relative to running. In a recent systematic review of resistance training and endurance cycling (Yamamoto et al. 2010), the results from five longitudinal studies that included high-level participants, appropriate training regimes and performance outcome measures were investigated (Table 2.6). Results were mixed, with two studies reporting no differences between the resistance and control group (Bishop et al. 1999, Jackson, Hickey and Reiser 2007), and three of the studies reporting significantly greater improvements in performance related measures in those exposed to resistance training (Hickson et al. 1988, Paton and Hopkins 2005, Bastiaans et al. 2001). Both studies that reported no significant differences between groups organised the experimental training by simply adding resistance workouts on top of a relatively heavy endurance training load. In contrast, studies that reported greater improvements in performance with resistance training attempted to substitute an equivalent portion of the athlete's regular endurance training. The authors of the systematic review hypothesised that without replacement an imbalance between the stimulus and accumulated fatigue was likely to have occurred and subsequently compromised the adaptive response (Yamamoto et al. 2010). No mechanisms were proposed to explain increases in performance in those studies reporting a positive effect from resistance training. However, in a recent study conducted with well-trained competitive cyclists it was shown that eight weeks of maximal strength training significantly improved cycling economy.(Sunde et al. 2010) Therefore, it appears that similar to endurance running, improvements in performance are obtained through improved efficiency. Future research is required to establish the specific adaptive responses that improve cycling economy in order to optimise the training regimes used with athletes.

**Table 2.6:** Review of longitudinal studies investigating the effects of resistance training with highly trained cyclists

| Author                   | Participants   | Training Protocol  | Outcome Measures                        | Findings  | Improvement  |
|--------------------------|--|--|---|---|--|
| Bastiaans et al. (2001)  | Trained male competitive cyclists (n=14). Completed a minimum of 10h/wk (13±3 h/wk). Allocated to treatment (n=6, 24±8 yr) and control (n=8, 29±12)                                      | 9 wk treatment: replaced a portion of endurance training with high repetition, low weight, explosive resistance training: 4x30 squats, 4x30 single-leg step-ups, 2x30 leg pull.  | 30 s STP, OHT                           | Treatment attenuated loss in STP from endurance training only | 7.1% increase in maximum power output in treatment group |
| Bishop et al. (1999)     | Endurance trained female cyclists. (n=21), 18-42 yr. Allocated to resistance training (n=14) and control (n=7)   | 12 wk treatment: In addition to endurance training performed resistance training 2d/wk. Performed periodized program of the back squat to failure.   | LT, $\dot{V}O_2$ peak, OHT              | 1RM CO squat increased. No change in outcome measures         | No between group differences in performance              |
| Hickson et al. (1988)    | Male and female [(n=6), (n=2)] endurance cyclists and runners  | 10 wk treatment: replaced a portion of endurance training with lower body resistance training with heavy loads (80% 1RM for 5 reps) in the squat, knee extension and hip flexion.  | STP, TTE                                | STP and TTE were improved with resistance training            | STP increased 11%, TTE increased 20%                     |
| Jackson et al. (2007)    | Male and female club trained cyclists [(n=18), (n=5)]. Minimum training load of 5hrs/wk. Allocated to high resistance (n=9, 31±10), high repetition (n=9, 32±9) and control (n=5, 27±10) | 10 wk treatment: In addition to endurance training performed resistance training 2d/wk. Non-periodized program. Squat, leg press, leg curls, single leg step-ups, high resistance 4x4 85% 1RM, low resistance 2x10 50% 1RM | LT, $\dot{V}O_2$ peak, TTE              | No change in outcome measures                                 | No between group differences in performance              |
| Paton and Hopkins (2005) | Male cyclists with a minimum of 3 years competitive experience. (n=18) Allocated to treatment (n=9, 22±8) and control (n=9, 24±9),   | 5 wk treatment: replaced a portion of endurance training with high repetition, low weight, explosive resistance training: vertical jumps and interval cycling  | LT, $\dot{V}O_2$ peak, 1 km TT, 4 km TT | Improved sprint and endurance performance gains               | 8.7% increase in 1 km power, 8.1% increase in 4 km power |

CO = concentric only, LT = Lactate threshold, OHT = 1 hour cycle test, STP = short term performance, TT = time trial, TTE = time to exhaustion,  $\dot{V}O_2$ peak = peak oxygen uptake,

In summary, it is now commonly recommended that athletes in virtually all sports perform resistance training to directly or indirectly improve performance. However, due to the complexity of many sports it remains difficult to quantify the impact that resistance training may have. An extensive research base has emerged to demonstrate that well-trained athletes can improve their ability to sprint and maintain high work-loads for extended periods when running or cycling by incorporating resistance training within their overall preparation. However, substantial increases in variables related to resistance training may be required to produce only modest improvements in performance. As running plays a major role in many sports the finding that resistance training can improve this ability highlights one area where the training could improve overall sporting performance. In addition, research demonstrating resistance training can improve performance of discrete sporting movements and create favourable changes in body composition further contributes to the growing evidence base from which to recommend the mode of training. The main focus for contemporary research in the field of resistance training and sports performance is to determine the most appropriate training protocols for each sport and ultimately each individual.

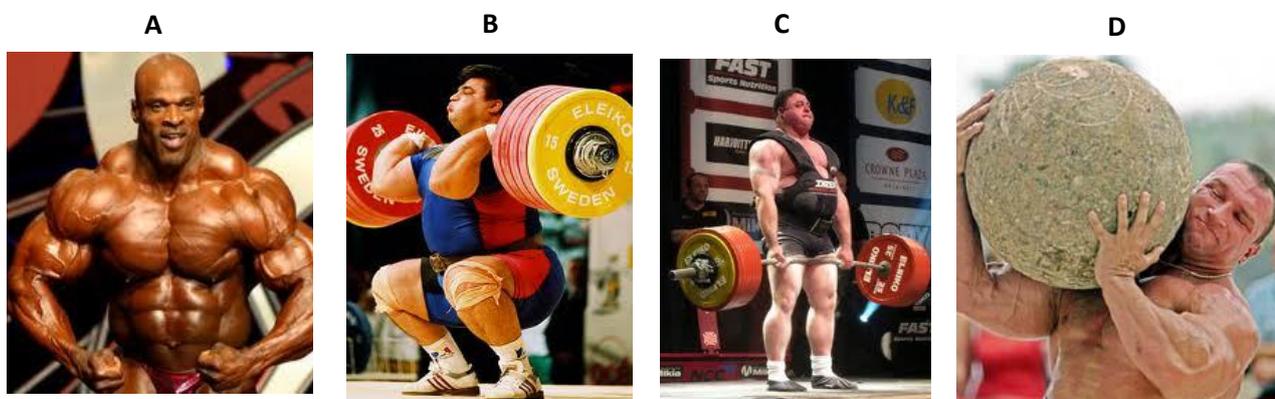
## **2.2 Strength athletes**

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As highlighted previously in this chapter, one of the major difficulties with prescribing resistance training is the creation of a regime from an almost unlimited number of possible configurations. Resistance training models are frequently used to assist in creating appropriate long-term training programmes; however, another approach which has been used since athletes began resistance training is to reproduce (to varying degrees) the programmes of the most experienced and successful resistance trained athletes. Collectively these individuals are referred to as strength athletes and comprise sportsmen and women whose training almost exclusively consists of resistance training. Four main groups of strength athletes including bodybuilders, Olympic weightlifters, powerlifters and strongmen are commonly recognised (Figure 2.2). These athletes are considered to be the strongest individuals in the world, yet a number of differences in morphology and function have been noted between the groups. It is the extensive but specific adaptations that each group obtains from training influenced by decades of trial and error that has led coaches and athletes to select what they perceive as the optimum training regime to develop a given attribute. Competitive bodybuilding has existed for over a century with modern athletes

exhibiting extreme muscular hypertrophy and low levels of adipose tissue (Fry and Newton 2002). In sports such as rugby and American football where body and total muscle mass are important and show increasing trends at rates far above the general population (Olds 2001), strength and conditioning coaches frequently incorporate training practices developed by bodybuilders (Gamble 2004). These practices generally involve stimulating different muscular groups of the body in separate sessions with the goal to create moderate forces and large acid-base disturbances (Siff 2003, Crewther, Cronin and Keogh 2006). In addition, a range of advanced training methods have been developed by bodybuilders which attempt to augment and manipulate the balance between force production and metabolic stress to create adaptations for individuals with extensive training experience (Kraemer and Fleck 2004, Siff 2003). Bodybuilders are the only group of strength athletes whose performance is not determined by their ability to lift heavy loads. As a result, it is often stated that bodybuilders train for aesthetics and not for function, and therefore athletes should only perform similar training practices in limited circumstances (Siff 2003). In a recent study conducted by Di Naso et al. (2012) a comparison of thigh muscle cross sectional area and strength measured during performance of the back squat was made between bodybuilders, Olympic weightlifters, and powerlifters. The athletes were all of similar mass with bodybuilders exhibiting a lower fat percentage and the largest muscle cross sectional area. However, the Olympic weightlifters and powerlifters were able to produce significantly greater forces despite their reduced muscle cross sectional area. The findings from Di Naso et al. (2012) support the hypothesis that training practices developed by bodybuilders may optimise the muscular hypertrophy response but are not the most effective for increasing force capabilities.

**Figure 2.2:** Representative images of elite A) Bodybuilders, B) Olympic weightlifters, C) Powerlifters, D) Strongman Athletes



Over the last thirty years interest in the training practices of Olympic weightlifters has steadily increased. Research conducted by Garhammer (Garhammer 1993, Garhammer 1980, Garhammer and McLaughlin 1980) demonstrated that extremely large force and power values Over the last thirty years interest in the training practices of Olympic weightlifters has steadily increased. Research conducted by Garhammer (1993, 1980a, 1980b) demonstrated that extremely large force and power values were generated when elite athletes performed either the snatch, clean and jerk, or any of the main variations of these movements. A large number of subsequent biomechanical studies have emphasised that non-elite athletes trained in the Olympic weightlifting movements can also produce large force and power values (Hori et al. 2008, Kawamori et al. 2005, Stone et al. 2006). As power is considered a key mechanical variable in the performance of many sporting tasks, the majority of researchers and coaches in the field of strength and conditioning currently recommend that most athletes perform the main Olympic weightlifting exercises and their close derivatives (Kawamori et al. 2005). In addition to the large power outputs, research has also established that the gross movement pattern used in the exercises are similar to many sporting actions that include rapid triple-extension of the hip, knee and ankle (Stone et al. 2006, Garhammer and Gregor 1992). However, despite the hypothesis that training with weightlifting movements can transfer effectively to improve athletic performance there have been concerns raised regarding the use of these exercises for general athletes (Bruce-Low and Smith 2007). These concerns generally relate to the perceived difficulty and time required to develop proficiency with the movements. In addition, a high potential for injury is often cited (Hedrick and Wada 2008). Biomechanical research conducted during competitions of elite weightlifters confirms that there is a range of demanding technical features associated with each of the movements (Gourgoulis et al. 2000, Kauhanen, Hakkinen and Komi 1984). However, research conducted with male lacrosse athletes demonstrated that technique could be improved with as few as twelve sessions when providing consistent verbal and visual feedback (Winchester et al. 2005). In addition, Comfort and colleagues (2012, 2011) have demonstrated that less technically demanding variations of the main weightlifting movements can be used to produce similar values for key kinematic and kinetic variables in both experienced and novice athletes. Determining the injury risk of a specific training practice is difficult due to confounding factors and the concurrent use of multiple types of training which is typical for most athletes. Evidence does show that soft tissue injuries of the wrists, shoulders, hip, back, knees and ankles are relatively common among individuals who engage in training with weightlifting movements (Hedrick and Wada 2008, Konig and Biener 1990). However, injury rates have been shown to be less than those obtained during other sporting activities such as American football, basketball and tennis for young athletes (Hamill 1994). In addition, it is unclear to what

extent injuries obtained during weightlifting are dependent upon improper exercise instruction and/or programming.

More recently, practitioners in the field of strength and conditioning have demonstrated interest in the training practices of strongman competitors and powerlifters. Interest in the sport of strongman represents a progression of the functional training perspective which has emerged over the last decade. In general, functional training seeks to enhance sporting performance by performing exercises that incorporate multiple segments of the body and often require large displacements in all three planes (Siff 2002). Whilst some researchers have criticised this approach on the basis of limited research and highly speculative theoretical underpinnings (Siff 2002), the functional training perspective remains the primary motivation for recommending strongman training for general athletes (Waller, Piper and Townsend 2003, Zemke and Wright 2011). The sport of strongman is distinct from other strength sports in that there is no set competition structure, and instead, a variable format is used with each competition featuring approximately 4 to 6 different events from a much larger repository. Each event is selected to test various attributes of the athlete's strength and endurance. Many of the activities require athletes to locomote with implements that are unbalanced and believed to represent a challenge that is distinct from traditional resistance exercises and therefore more likely to transfer to sporting performance (Zemke and Wright 2011). To test this hypothesis, McGill et al. (2009) compared resisted locomotive activities performed in strongman competitions with more traditional lifting tasks using a world-class competitor. EMG and electromagnetic tracking of the body were used to assess muscular activity and loads experienced around the trunk. The results demonstrated that there were significant differences between the two types of tasks with greater lumbar loads and trunk stiffness created during the resisted locomotive activities. Analyses revealed that differences were caused by greater co-contraction of trunk muscles during the more mobile activities to protect the spine. The authors concluded that the distinct biomechanical stimulus created provided a rationale to include the unique activities of strongman in the training of general athletes (McGill, McDermot and Fenwick 2009). Additional cross-sectional research from various strongman activities including car pulling (Berning et al. 2007) and tyre flipping (Keogh et al. 2010) has shown that very high physiological stress is created, providing support for practitioners that recommend the training to improve the anaerobic conditioning of athletes (Waller, Piper and Townsend 2003, Hedrick 2003). Further biomechanical and physiological research is required with general athletes performing strongman activities to determine if constructive stimuli and subsequent beneficial adaptations can be obtained.

In contrast to the relatively new appreciation of the potential benefits associated with strongman activities, the resistance training practices of general athletes have been influenced by powerlifters for a much longer period of time. The first powerlifting competitions were held in the 1960s in North America (Fry and Newton 2002). Competitors were separated into categories based on body mass and given three attempts to lift the heaviest load possible in the squat, bench press and deadlift. These exercises were selected to provide a measure of the athletes total body strength. Based on the extremely heavy loads that could be lifted with each movement and the large forces produced, the first strength and conditioning coaches replicated many of the training practices used by powerlifters with their own athletes (Todd 1994). Since the initial competitions, the training methods of powerlifters developed and continued to influence the design of maximum strength regimes of other athletes. However, until recently, the development of training practices used by powerlifters appeared to be relatively unaltered and featured only small changes in the design of training cycles. With the rapid proliferation of internet sites dedicated to powerlifting, several novel training practices are now promoted. Examples include the use of unconventional barbells, resistance in the form of chains and bands, and the performance of fast velocity repetitions with sub-maximum loads (Simmons 2007, Tate 2006). At the same time novel training practices have been promoted, there has been a large increase in the competitive standard of powerlifting. Over the last decade world best performances in the squat and bench press in particular have dramatically increased. Some individuals have advocated a cause and effect relationship between recent developments in powerlifters training practices and improved performances (Tate 2006). This possibility has led many strength and conditioning coaches to incorporate the practices within their athlete's resistance training regimes. At present it is not known whether the novel training practices have caused the recent improvements in powerlifting or will be beneficial for general athletes. It is important to acknowledge that there are many factors that could have contributed to improved performances in powerlifting including increases in participant numbers, rule changes, advancements in ergogenic equipment, use of nutraceutical and pharmacological agents, etc. In addition, it is unclear which training practices are actually used by successful powerlifters as financial incentives and sponsorship may influence the information presented.

Researchers in sport and exercise science have begun to investigate some of the most widely promoted contemporary training practices used by powerlifters. The majority of the research conducted thus far has compared the biomechanical stimulus created during novel practices with that produced during more traditional training (Ebben and Jensen 2002,

McBride et al. 2010, Doan et al. 2002). Biomechanical research appears to be particularly well suited for this area of investigation, based on the rationales that have been proposed to account for the apparent success of the novel training practices. Indeed, many forms of training associated with maximum strength and power development involve muscular actions over relatively short durations and therefore are unlikely to induce extensive acute metabolic and hormonal responses that would warrant the interest of physiologists. Instead, the proposed success of the novel training practices and other approaches focused on developing strength and power are considered most influenced by their potential to maximise biomechanical variables (e.g. force, impulse, work, power acceleration) (Crewther, Cronin and Keogh 2005), or to activate specific muscle groups and limb movements related to performance in sporting tasks (Siff 2003). The following sections of the literature review discuss in greater depth the development and use of biomechanics research as a means of investigating resistance training practices. The following sections also include discussion of the theoretical frameworks that underpins much of the research for this PhD.

## **2.3 Application of Biomechanics**

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### **2.3.1 Traditional applications**

Traditionally, the application of biomechanics to resistance training has been viewed from the perspectives of technique analysis and fundamental mechanical concepts. The technique analysis approach has been used widely by sports biomechanists in all fields, and has been adopted in the study of resistance training mainly to inform exercise selection (Knudson 2003). In particular, technique analysis has been used to assess the benefit-to-risk ratio of particular movements, and to determine which exercises are most sport-specific (Knudson 2003). Both qualitative and quantitative approaches have been used extensively when analysing exercise techniques. The squat has been the most widely investigated resistance training exercise as it is viewed as the most popular and important for developing strength and power, but has also been perceived to present a significant injury risk (Chandler and Stone 1991). Qualitative analyses of squat technique generally section the movement into phases and evaluate performance on adherence to key technical points (examples are displayed in Table 2.7) (Baechle and Earle 2008), which are based on principles of movement and data gathered from quantitative studies. For example, bar

position is selected as a key technical point on the principle of torques and the subsequent resistive moments experienced at the hip and lower back; whereas the recommended neutral spine position is influenced by research reporting that flexed postures reduce the extensor component of the muscle force and limit capacity to resist anterior shear forces at the lumbar spine (McGill, Hughson and Parks 2000).

**Table 2.7:** Key technique points for the squat

| Starting position   | Downward movement   | Upward movement  |
|---|---|--|
| Grasp the bar with a closed, pronated grip in one of two positions:   | Maintain a position with the back flat, elbows high and the chest up and out  | Maintain a position with the back flat, elbows high and the chest up and out           |
| 1) High bar position – above the posterior deltoids at the base of neck (handgrip slightly wider than shoulder width)   | Allow the hips and knees to flex slowly whilst maintaining the torso-to-floor angle relatively constant                                   | Extend the hips and knees at the same rate (to keep the torso-to-floor angle constant) |
| 2) Low bar position – across the posterior deltoids at the middle of the trapezius (handgrip wider than shoulder width) | Keep the heels on the floor and the knees aligned over the toes   | Keep the heels on the floor and the knees aligned over the toes                        |
| Lift the elbows up with chest up and out, Tilt the head slightly up   | Continue flexing the hips and knees until the thighs are parallel to the floor, the trunk begins to round or the heels rise off the floor | Continue extending the hips and knees to return to the starting position               |
| Position the feet shoulder width apart with the toes pointed slightly outward   | Do not bounce at the bottom of the movement   | Ensure that the knees and hips are fully extended and not hyper-extended               |

Adapted from: Baechle, T.R. Earle, R.W. (2008). *Essentials of strength training and conditioning*. Human Kinetics, Champaign, IL. pgs 350-351.

Quantitative analyses of any movement require the selection of key variables (Lees 2002). When evaluating the benefit-to-risk ratio of resistance training exercises the key variables have traditionally included the measurement of joint torques to assess muscular effort and joint forces to assess injury potential. For the squat, quantitative analyses have generally focused on the knee where injury concerns are greatest (Chandler and Stone 1991, Schoenfeld 2010). Measurement of joint forces at the knee have revealed extremely large compressive forces of up to 8000 N (Nagura et al. 2002) and shear forces of up to 2700 N (Donnelly, Berg and Fiske 2006) with values increasing at greater flexion angles. Using more advanced mechanical models and integrating EMG, estimates of soft tissue forces have also been made (Escamilla et al. 2001b). Results from these models have shown that anterior and posterior cruciate ligament forces are relatively low at high knee flexion angles (Li et al. 2005), whereas patellar tendon forces are at their greatest (Nagura et al. 2002). As a result of the high compressive and shear forces that can be obtained most technical recommendations suggest that maximum knee flexion during the squat should not exceed 50 to 60°, with increased angles adopted if it is required for specific conditioning in a sport or to assist performance in other exercises that require almost full flexion (Schoenfeld 2010, Comfort and Kasim 2007).

Quantitative research conducted at the hip joint during squatting has tended to focus on muscle recruitment and the relationship between kinematics and kinetics rather than joint forces. Research conducted by Fry et al. (2003) demonstrated that significant changes to hip net joint torques were obtained when participants were forced to change the joint angle relationship between the hip, knee and ankle. Additionally, measurement of EMG activity of the musculature surrounding the hip has been shown to be influenced by squat depth as well as stance width. Caterisano et al. (2002) reported that gluteus maximus activity increased significantly when squats with large amounts of hip flexion were compared with shallower repetitions. McCaw and Melrose (1999) also found that wider stance widths elicited greater EMG activity values from the hip extensor muscles, with the greatest activity measured with repetitions performed at 140% of shoulder width. Collectively, the extensive biomechanical research that has been conducted on the squat indicates that the exercise does have a high benefit-to-risk ratio and that specific guidelines can be created for individuals who suffer certain pathologies or seek to manipulate the stimulus to focus on certain muscular groups of the body.

A substantial research base comprising biomechanical investigations has also been created for exercises such as the bench press, deadlift and more recently Olympic weightlifting exercises. Many of the biomechanical studies conducted on the clean and snatch exercises have assessed the techniques employed by elite athletes (Gourgoulis et al. 2000, Kauhanen, Hakkinen and Komi 1984, Enoka 1988, Baumann et al. 1988). This research has documented variables such as critical joint angles, joint movement patterns and barbell kinematics to create a model template for non-weightlifters to follow. The use of model templates in general has been criticised because of the unsupported assumption that success equates with technique and the contention that model templates discourage critical thought (Lees 2002). With specific reference to weightlifting exercises, it may be unreasonable to expect athletes from other sports to be able to duplicate the movements created by elite specialists with years of specific conditioning. In particular, the extensive range of motion adopted at many joints under high loads by elite weightlifters, may serve as inappropriate models for many general athletes.

Traditional applications of biomechanics to resistance training have also used knowledge of fundamental mechanical concepts to manipulate various features of exercises. In the majority of strength and conditioning text books a chapter is typically dedicated to discussing the role of biomechanics, featuring topics such as mechanical levers, resistance movement arms, and the different forms of resistance commonly used in practice (Stone, Stone and Sands 2007, Baechle and Earle 2008, Cardinale, Newton and Nosaka 2011). Many of these topics rarely feature in isolation in peer reviewed research; however, they are extremely important to the profession and are used on a daily basis by trained strength and conditioning coaches. The ability to manipulate the resistance moment arms created during performance of an exercise is an important aspect of managing injury risk (Stone, Stone and Sands 2007). As a result, the key technical points of most exercises provide guidelines for the placement of the load relative to each segment of the body (Baechle and Earle 2008). Different forms of resistance discussed in textbooks and biomechanics reviews generally include free weights, pulleys, levers and cams, hydraulic resistance and pneumatic resistance (Stone, Stone and Sands 2007, Frost, Cronin and Newton 2010). Machines that incorporate resistances that can vary throughout the movement are very popular in health facilities, however, they are rarely recommended for the purposes of athletic training. This is because resistance training machines generally restrict movement to a single plane, and, therefore, are considered ineffective for transferring improvements to sporting activities (Frost, Cronin and Newton 2010). In addition, it is argued that the relatively fixed nature of resistance training machines limits the development of balance and

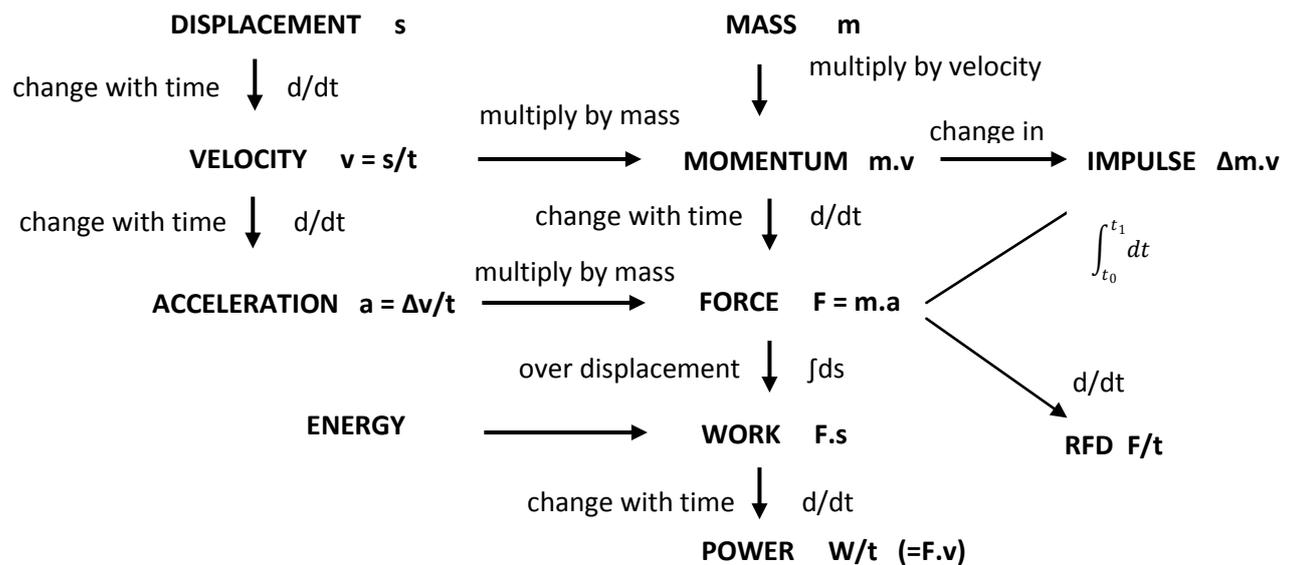
proprioceptive abilities that are important in complex sporting tasks (Kraemer and Fleck 2004). One exception appears to be the use of cable-pulleys which generally provide more than a single dimension of motion, and are frequently recommended for training the muscles of the trunk (Waller 2004) and for performing exercises which are kinematically similar to actual sporting movements (Tvrđy 2011, Roetert, Knudson and Groppe 2009), which, as discussed above is a key feature of traditional applications of biomechanics.

### **2.3.2 The variable based approach**

The biomechanical approach used in contemporary resistance training research has largely moved from technique based evaluations to the measurement of key kinematic and kinetic variables (Figure 2.3). This approach has been used extensively to determine the exercises best suited for development of specific athletic qualities and/or fitness variables, which as discussed in previous sections of this literature review, is an important component in models of resistance training. A variety of methodological approaches have been used to assess which mechanical variables are important for performance in different sports. Generally, the approaches used include 1) rank order studies; 2) correlation studies; and 3) longitudinal studies (Stone, Moir and Sanders 2002, Cronin and Sleivert 2005). Rank order studies (or “best vs. the rest” in some publications) compare elite with non-elite athletes in their ability to express mechanical variables hypothesised to impact on performance. If the variable is related to sporting performance, then a difference in the ability to express that variable should be found between those that perform the sport best (elite athletes) and those whose performance is at a lower level (non-elite athletes). The Northern American collegiate system provides an effective model to test rank order hypotheses. Colleges are separated into three divisions with regards to the quality of their sports teams. Division I colleges comprise the largest universities and are able to attract the most talented sportsmen and women with the most desirable scholarships. Division II and division III colleges attract progressively less talented individuals, respectively. Rank order studies across a range of sports have demonstrated that higher division athletes are able to produce significantly greater maximum force, power and RFD values than their less talented counter-parts (Fry and Kraemer 1991, Hansen et al. 2011a, Gissis et al. 2006, Ho, Smith and O’Meara 2009). The rank order approach, however, cannot establish cause and effect as differences in performance capabilities could be caused by other factors (that may be related to the mechanical variables). Information gained from rank order studies can be used as part of a larger body of evidence to provide support for, or contradict a specific hypothesis. In

addition, the approach can be used inductively to generate hypotheses that can then be tested with different research designs.

**Figure 2.3:** Summary of the major concepts used in the variable based biomechanical analysis of resistance training



The correlation approach is similar to that used in rank order studies, insofar as both can provide indirect evidence of the importance of a variable in relation to performance; however, neither can be used to establish cause and effect. Correlation studies may provide slightly more robust evidence as the strength of relationships can be expressed quantitatively. In comparison, there is no set method to interpret how large differences must be between levels in rank order studies to represent a meaningful result. However, calculation of effect sizes may be one method to complement the inferential statistics. An additional advantage of the correlation approach is that the shared variance can be calculated to provide an estimation of the proportion of total variance in one variable (e.g. measure of performance) that can be explained, or accounted for, by the variance in another (e.g. power) (Thomas, Nelson and Silverman 2010). The major difference between correlation studies and the rank order approach is based on the measurement of performance. In the rank order approach it is assumed that higher level athletes are better performers, but in general, differences between levels are not quantified. In contrast, correlation studies require some measurement of performance to complete the analysis. As discussed in section 2.1.3, direct measurement of performance in many sports is not possible. Instead, researchers have frequently used performance related tests of jumping,

sprinting and change of direction to act as proxies. In reality, these tests provide measures of athleticism, with the potential that performance in these tests may relate to performance in various sports. The results of correlation studies investigating the relationship between athletes' ability to produce values in different biomechanical variables and their performance in athletic tests have been mixed, with factors such as the population studied and combination of predictor (biomechanical variable) and outcome (performance related) tests influencing results.

The most widely investigated biomechanical variable has been maximum strength. Initial research quantifying the relationship between isometric tests of maximum strength and dynamic performance measured from jumping tests revealed only weak to moderate correlations (Murphy, Wilson and Pryor 1994, Guy et al. 1996). Much stronger correlation values have been obtained for maximum strength measurements made during exercises such as the back squat. Correlation values as high as  $r = 0.94$  (Wisloff et al. 2004) and  $r = 0.92$  (Peterson, Alvar and Rhea 2006) have been obtained for 1RM squat scores and tests of sprinting and jumping, respectively. Discrepancy in correlation values obtained for isometric or dynamic measurements of strength with performance have been proposed to reflect the neural and mechanical differences associated with each type of action (Wilson and Murphy 1996). However, weaker and non-significant correlation values have also been reported by studies correlating dynamic measurements of strength with performance. Cronin et al. (2003) reported a nonsignificant correlation value of  $r = 0.24$  between maximum strength measured during a supine squat movement and performance in an explosive lunge exercise selected to simulate a common movement in team sports. Using a group of well trained athletes, Wilson et al. (1995) reported correlation values for twenty different force-time variables collected during a jump squat and sprint performance as measured by a 30 m test. Maximum force exhibited a trivial correlation of  $r = 0.04$ , with the strongest correlations reported for variables reflecting the ability to produce high forces in short time periods ( $r = 0.45$  to  $r = 0.62$ ). It is likely that the major factor influencing the strength of correlations obtained with similar predictor and outcome tests is the population recruited. Studies that have recorded very strong correlations have generally featured heterogeneous samples exhibiting considerable variation in strength and performance capabilities. With more homogenous samples, factors other than strength may become more important in distinguishing performance scores.

Correlation studies have also been used to investigate the relationship between different mechanical variables. Using elbow flexions performed with isoinertial loads, Moss et al. (1997) investigated the relationship between maximum strength and power in a group of well-trained male physical education students. The authors reported a very strong correlation between maximum strength and maximum power ( $r = 0.93$ ), with a substantially lower, but still strong correlation found between maximum strength and power produced with minimal external loading ( $r = 0.73$ ). Similar relationships between strength and power were reported by Stone et al. (2003a). The authors measured power during jumps squats performed on force platforms with loads of 10 to 100% 1RM. The strongest correlation was obtained between 1RM and peak power obtained with 50% 1RM ( $r = 0.94$ ). A strong correlation was also obtained between 1RM values and power measured during repetitions performed with 10% 1RM ( $r = 0.84$ ). In the studies conducted by Moss et al. (1997) and Stone et al. (2003a) the strong correlations were obtained with heterogeneous populations. Participants recruited by Stone et al. (2003a) had training experience that ranged from seven weeks to over fifteen years. Studies with more homogenous populations have obtained lower, but also strong and significant correlations between strength and power. Across three studies conducted with high-level rugby league players, Baker and colleagues (2001) obtained correlations of 0.79, 0.81 and 0.86 between 1RM and maximum power values measured during the jump squat. The coefficient of determination obtained in these studies range from 63 to 75%, demonstrating that a large amount of the variance in power capabilities across the athletes can be explained by maximum strength, and vice versa.

Correlations between other popular mechanical variables have generally been moderate to strong, but lower than those reported for maximum strength and power. McLellan et al. (2011) investigated the intercorrelation of force-time variables obtained during performance of a vertical jump. Peak force and RFD demonstrated relatively strong correlations ( $r = 0.63$ , vs.  $r = 0.86$  for peak force and power). The strength of relationships between power and RFD variables were mixed, and ranged from  $r = 0.36$  to 0.73 depending on whether it was average or peak values that were analysed. In a study conducted by Cronin et al. (2003) investigating a wide range of force-time variables (e.g. peak force, impulse, power, average RFD, force produced at particular time intervals) correlation values ranged from 0.43 to 0.99, with all reaching statistical significance. Collectively, the results demonstrate that there is a degree of relatedness between most mechanical variables, which may reflect either athletes' diverse training practices or a generality in the outcome of training adaptations induced by resistance training.

Longitudinal studies provide an important extension to cross-sectional research as they can provide better understanding of cause and effect relationships. However, most longitudinal studies incorporating resistance training interventions are of short duration (i.e. 4 to 12 weeks) and feature relatively untrained participants. These design limitations reduce the explanatory power of the studies and limit their application to sport, where measurable improvements in high-level athletes generally require much longer time periods (McGuigan and Kane 2004, McGuigan, Cormack and Newton 2009, Appleby, Newton and Cormie 2012, Anderson et al. 2006). In section 2.1.3 of this literature review, a number of frequently cited longitudinal studies investigating the effects of resistance training on sprinting, running and cycling were discussed. Unfortunately, the majority of these studies and others have failed to include correlation analyses across the intervention to quantify the relationship between improvements in biomechanical variables (e.g.  $\Delta 1RM$ ,  $\Delta power$ ,  $\Delta RFD$ ) and improvements in performance. This additional feature would provide more robust evidence of which biomechanical variables are most important in the improvement of various sporting tasks. Instead, researchers have mainly tracked changes in biomechanical and performance variables across the intervention period, with correlations between predictor and outcome variables re-assessed at each data collection stage (Stone et al. 2003b, Robinson et al. 1995). This approach enables researchers to determine if the relationship between mechanical variables and performance is influenced by relatively short-term adaptations to resistance training. However, greater understanding of the effect of different mechanical variables on sports performance would be obtained if future longitudinal studies included correlation analyses (or related statistical techniques) between changes measured in variables.

Once evidence has been obtained to indicate that a specific mechanical variable is important to the performance of a particular skill or sport, the field of biomechanics is also used to determine the most effective training practices to improve an athlete's ability to produce high values in the variable. The process is based on one of the most influential paradigms in contemporary strength and conditioning, namely, that the best training stimulus is created by selecting acute program variables that maximise production of the biomechanical variable targeted. That is, maximum strength, power and RFD are most effectively improved by selecting exercises, loads, repetitions and rest periods that maximise the acute production of force, power or RFD, respectively. Whilst it is recognised that short-term changes created from a wide range of exercise stimuli can accrue over time

to create similar positive adaptations (and importantly, that variation in training is required for continued improvements) (Stone, Stone and Sands 2007), data does exist to support the paradigm. For the development of maximum strength, Zatsiorsky (1995) has promoted the use of the maximal effort method. This requires the performer to select exercises that incorporate large muscle groups and produce high motivation to lift the heaviest loads possible for one to three repetitions. This training practice ensures that individuals produce maximum or close to maximum forces to stimulate adaptations to the central nervous system.

One of the first studies to systematically investigate the optimum resistance for the development of strength was conducted by Berger (1962b). Incorporating a college class of 199 male students, participants were allocated to one of six groups for a twelve week training intervention to improve upper body strength as measured by the bench press. The groups performed one bench press set comprising 2, 4, 6, 8, 10 or 12 repetitions to failure, three times per week. Analysis of covariance revealed differences between the groups with the greatest increases in strength obtained with those performing 4, 6 or 8 repetitions each set. The results obtained by Berger (1962b) suggest that strength is best improved by moderate loading and therefore the development of forces that are less than maximum. However, the group lifting the heaviest load only performed 6 repetitions per week which is unlikely to provide an adequate metabolic and hormonal stimulus to create adaptations and is not representative of the high force training commonly used to increase strength.

More recent studies investigating the optimum training strategies to improve strength have demonstrated a clear distinction between the requirements of novice and advanced individuals, with those previously untrained obtaining significant increases in strength whilst producing low forces with loads as light as 45 to 50% 1RM (Anderson and Kearney 1982, Campos et al. 2002). In contrast, research conducted by Hakkinen et al. (1985) with experienced resistance trained males showed that over a twenty four week training period incorporating resistances ranging from 70 to 120% 1RM, increases in strength required the production of near maximum forces with training loads of at least 80% 1RM. In addition, further support for the advantages conferred by training that develops large forces is found in research using the meta-analysis approach. Peterson et al. (2004) performed a literature search for studies including a strength training intervention with resistance trained athletes. A total of thirty seven studies were included in the final analysis. Pre-post effect sizes were used to standardise the improvement in strength obtained over the intervention. The results

demonstrated that training regimes incorporating training loads of 85% 1RM resulted in substantially greater improvements than those using lighter resistances. A lack of sufficient data to investigate loads above 85% 1RM meant that the authors were unable to determine if even greater results may have been obtained with training that produced higher forces. Collectively, research conducted with trained individuals focusing on strength strongly supports the paradigm that improvements are best obtained with training that maximises acute production of the variable of interest.

In contemporary strength and conditioning, the variable that receives the most interest with regard to the development of athletes is power. This is because the ability to develop large power values is considered essential to perform at a high level in most sports (Bevan et al. 2010, Sleivert and Taingahue 2004, Dayne et al. 2011). As discussed above, evidence does exist to support this position. However, it is possible that the perceived importance of power is influenced to some extent by the use of the term in common language rather than the unambiguous mechanical definition. In accordance with the paradigm of maximising the acute expression of a variable for optimal adaptations, many researchers and practitioners have recommended that athletes train with exercises, loads and repetitions schemes that produce the greatest peak power values (Sleivert and Taingahue 2004, Baker and Nance 1999, Kaneko et al. 1983, Newton and Kraemer 1994, Stone 1993). In contrast to the relatively simple protocols that can be followed to express maximum force, the production of maximum power values is considerably more complex. Research has shown that power is maximised in single muscle fibres and single-joint movement when the resistance creates force values that are approximately 30% of maximum (Kaneko et al. 1983, Toji and Kaneko 2004, Faulkner, Clafin and McCully 1986). However, with multi-joint exercises the protocols that maximise power are dependent upon a number of factors, the most important of which is the load used. Indeed, the identification of the load that maximises power has attracted more biomechanics research than any other topic in the field of strength and conditioning (Table 2.8). This extensive research base has demonstrated that the load that maximises power is also dependent upon a number of factors. The exercise selected has been shown to be the most influential, with the optimal load ranging from 0 to 40% 1RM for ballistic exercises such as the jump squat and bench throw, 30 to 60% 1RM for the traditional squat and bench press, and 70 to 90% 1RM for Olympic weightlifting movements such as the clean and snatch. In addition to exercise selection, the training status of the individual and methods used to calculate power has also been shown to influence the load that maximises power. Using both countermovement and static jump squats, Stone et al. (2003a) reported that participants with lower maximum strength produced maximum power values with the

lightest load equal to 10% 1RM, whereas stronger participants produced maximum power for both vertical jump conditions with 40% 1RM. Studies conducted by Driss et al. (2001) and Baker et al. (2001b) also reported that stronger athletes produce maximum power with greater relative resistances than their weaker counterparts. However, conflicting evidence indicating that the optimum load for power production is not influenced by an individual's strength also exists (Cormie, McGuigan and Newton 2010b, Nuzzo, McBride and Dayne 2010). Further comparative research is required to clarify the role, if any, of maximum strength on the load-power relationship.

More recently, research has highlighted that the methods used to calculate power can influence the load-power relationship. Michael et al. (2008) reported that calculations based entirely on movement of the barbell underestimates the total power developed and shifts the optimum load to greater relative resistances. In contrast, calculations of power that combine the ground reaction force and barbell kinematics have been reported to overestimate power (Michael, Olson and Winchester 2008, Lake, Lauder and Smith 2012) and may cause a shift in the optimum load towards lower resistances where the barbell velocity is substantially greater than the velocity of the system COM.

**Table 2.8:** Loads that maximise power production in various exercises

| Authors                 | Participants  | Exercises   | Power Test Protocol   | Maximum Load   |
|-------------------------|---|---|---|--|
| Alcaraz et al. (2011)   | Male sprinters (n=10). 22.1±3.6 yr.   | Max: 1RM SSC smith squat<br><br>Power: SSC smith squat  | SSC smith squat with 30/45/60/70/80% 1RM.   | 60% 1RM, no SD across loads tested                                       |
| Asci and Acikada (2007) | Male (sprinters, basketball, handball, volleyball, bodybuilders) (n=56). 23.7±4.7 yr.   | Max: 1RM CO bench press<br><br>Power: CO bench press  | CO bench press with 40/50/60/70/80% 1RM   | 50% 1RM, no SD across 40-60% 1RM   |
| Baker and Nance (1991)  | Professional male rugby league players (n=20). 24.2±3.8 yr.   | Max: 3RM SSC free weight squat<br><br>Power: Smith Jump Squats  | SSC smith jump squat with absolute loads 40/60/80/100 kg  | 100kg (≈65% 3RM), no cross load analysis                                 |
| Baker et al. (2001)     | Male rugby players, professional (n=18) and semi-professional (n=13). Considered as one group (no significant differences). 22.2±3.5 yr | Max: 1RM free weight Bench Press<br><br>Power: Smith bench press throw  | SSC Smith Bench Press with absolute loads. 40/50/60/70/80 kg.   | 70 kg (≈55% 1RM), no SD across 70-80 kg                                  |
| Baker (2001)            | Amalgamation of data from multiple studies of professional rugby league players and semi-professional rugby league players.             | Max: 1RM free weight squat.<br><br>Max: 1RM free weight bench press.<br><br>Power: SSC smith jump squats.<br><br>Power: SSC smith bench press throw | SSC smith jump squat with absolute loads. 40/60/80/100 kg.<br><br>SSC smith bench press with absolute loads. 40/50/60/70/80 kg. | ≈55% 1RM, no cross load analysis<br><br>≈55% 1RM, no cross load analysis |
| Bemben et al. (1991)    | College-aged men (n=31)   | Max: 1RM free weight bench press.<br><br>Power: free weight bench press   | SSC bench press with 30/40/50/60/70/80%1RM  | 50% 1RM, no cross load analysis  |

|                       |  |   |  |  |
|-----------------------|--|---|--|--|
| Bosco et al. (1995)   | Male and female track and field athletes (n=33), male and female throwers (n=12), male and female jumpers (n=21). 21.6±4.6 yr. | Max: 1RM SSC free weight squat<br><br>Power: SSC free weight squats   | SSC squats with loads relative to body mass.<br>35/70/100/105/140/175/210% BM  | Males and females 105% BM, no cross load analysis  |
| Comfort et al. (2012) | Male athletes with resistance training experience (n=19). 21.5±1.4 yr.   | Max: 1RM power clean from the hang<br><br>Power: 1RM power clean from the hang  | Hang power clean with<br>30/40/50/60/70/80% 1RM  | 70% 1RM, no SD across 60-80% 1RM   |
| Cormie et al. (2007)  | Male division I athletes (sprinters, football players, long jumpers) (n=12). 19.8±1.4, yr                                      | Max: 1RM free weight squat<br><br>Max: 1RM power clean<br><br>Power: SSC free weight squat<br><br>Power: power clean<br><br>Power: free weight SSC jump squat | Squat with<br>0/12/27/42/56/71/85% 1RM<br><br>Jump squat with<br>0/12/27/42/56/71/85% 1RM<br><br>Power clean with<br>30/40/50/60/70/80&90% 1RM | 56% 1RM, no SD across loads tested<br><br>0% 1RM, no SD across 0-27% 1RM<br><br>80% 1RM, no SD across loads tested |
| Cronin et al. (2000)  | Male athletes with resistance training experience (n=27). 21.9±3.1, yr   | Max: 1RM SSC smith bench press<br><br>Power: SSC smith bench press<br><br>Power: CO smith bench press   | SSC smith bench press with<br>40/60/80% 1RM<br><br>CO smith bench press with<br>40/60/80% 1RM  | 40-60% 1RM<br><br>40-60% 1RM   |
| Cronin et al. (2007)  | Elite male rowers (n=8). 25.2±3.8 yr.  | Max: 1RM cable seated row<br><br>Power: cable seated row  | Cable seated row with<br>30/40/50/60/70/80/90/100% 1RM   | 80% 1RM average power<br><br>60% 1RM peak power<br><br>no cross load analysis                                      |

|                            |  |   |  |   |
|----------------------------|--|---|--|---|
| Dayne et al. (2011)        | High school male athletes (n=11). 15.6±0.5 yr.   | Max: 1RM SSC free weight squat<br><br>Power: SSC free weight jump squat   | SSC free weight jump squat with 0/20/40/60/80% 1RM   | 0% 1RM  |
| Frost et al. (2008)        | Recreationally weight trained males (n=30). 24.9±4.9 yr.   | Max: 1RM SSC smith bench press<br><br>Power: SSC smith bench press<br><br>Power: SSC smith bench press throw                  | SSC smith bench press with 15/30/45/60/75/90% 1RM<br><br>SSC smith bench press throw with 15/30/45/60/75/90% 1RM | 45% 1RM<br><br>15% 1RM<br><br>no cross load analysis                                      |
| Harris et al. (2007)       | Male rugby athletes (n=18). 23.1±2.7 yr.   | Max: 1RM SSC machine squat<br><br>Power: SSC machine squat jump   | SSC machine squat jump with 10/20/30/40/50/60/70/80/90/100% 1RM  | 20%1RM peak power<br><br>40% 1RM average power<br><br>no cross load analysis              |
| Izquierdo et al. (2002)    | Male athletes (weightlifters, handball players, road cyclists, middle distance runners) (n=68) and controls (n=12). 21.4±4.7 yr. | Max: 1RM CO smith squat.<br><br>Max: 1RM CO smith bench press<br><br>Power: CO smith squat<br><br>Power: CO smith bench press | CO smith squat bench press: 30/45/60/70/80/100%<br><br>CO Smith bench press: 30/45/60/70/80/100%                 | 30-60% 1RM<br><br>30-45% 1RM  |
| Jandaka and Uchytíl (2011) | Professional male soccer players (n=15). 26.1±3.9 yr.  | Max: 1RM SSC smith bench press<br><br>Power: SSC smith bench press  | SSC smith bench press 0/10/30/50/70/90% 1RM  | 50% 1RM   |
| Kawamori et al. (2005)     | Male athletes with resistance training experience (n=15). 22.1±2.0 yr.   | Max: 1RM hang power clean<br><br>Power: Hang power clean  | Hang power clean with 30/40/50/60/70/80/90% 1RM  | 70% peak power, no SD across 50-90% 1RM<br><br>70% average power, No SD across 40-90% 1RM |

|                        |  |  |   |  |
|------------------------|--|--|---|--|
| Newton et al. (1997)   | Recreationally weight trained males (n=17). 20.6±1.9 yr.                           | Max: 1RM SSC Smith Bench Press.<br><br>Power: SSC smith bench press Throw<br><br>Power: CO Smith Bench Press Throw                                 | SSC Smith Bench Press Throw: 15/30/45/60/75/90% 1RM<br><br>CO Smith Bench Press Throw: 15/30/45/60/75/90% 1RM                       | 15% 1RM peak power<br>45% 1RM average power<br><br>15% 1RM peak power<br>30% 1RM average power<br><br>no cross load analysis   |
| Siegel et al. (2002)   | Recreationally weight trained males (n=25). 23±4 yr.                               | Max: 1RM SSC Smith Squat<br><br>Max: 1RM SSC Free-Weight Bench Press<br><br>Power: SSC Smith Squat<br><br>Power: SSC free weight bench press       | SSC Smith Squat and 30/40/50/60/70/80/90% 1RM<br><br>SSC Free weight bench press 30/40/50/60/70/80/90% 1RM                          | 50-70% 1RM<br><br>40-60% 1RM   |
| Sleivert et al. (2004) | Male athletes. (power, rugby and basketball) (n=30). 2.4±1.4 yr.                   | Max: 1RM Smith CO Squat<br><br>Max: 1RM Smith CO Split Squat<br><br>Power: CO Power Smith Squat Jump<br><br>Power: CO Power Smith Split Squat Jump | CO Power Smith Squat Jump 30/40/50/60/70% 1RM<br><br>CO Power Smith Split Squat Jump 30/40/50/60/70% 1RM                            | 60% 1RM peak power, no SD across loads<br><br>40% 1RM average power, no SD across 30-60% 1RM<br><br>40% 1RM peak power, no SD across 30-50% 1RM<br><br>50% 1RM average power, no SD across |
| Stone et al. (2003)    | Male participants with extensive range of training experience (n=22). 22.2±3.8 yr. | Max: 1RM SSC free weight<br><br>Power: SSC Free-Weight Jump Squat<br><br>Power: CO free weight jump  | SSC Free-Weight Jump Squat 10/20/30/40/50/60/70/80/90/100% 1RM<br><br>CO Free-Weight Jump Squat 10/20/30/40/50/60/70/80/90/100% 1RM | 10% 1RM<br><br>10% 1RM<br><br>no cross load analysis   |

|                      |   |   |  |   |
|----------------------|---|---|--|---|
|                      |   | squat   |  |   |
| Thomas et al. (2007) | Male (n=19) and female (n=14) division I athletes. 19.5±1.5 yr. | Max: 1RM Smith SSC bench<br><br>Max: 1RM Smith SSC squat<br><br>Max: 1RM Smith hang high-pull<br><br>Power: Smith SSC bench throw<br><br>Power: Smith SSC squat jump<br><br>Power: Smith hang high-pull | Smith SSC bench throw with 30/40/50/60/70% 1RM<br><br>Smith SSC squat jump with 30/40/50/60/70% 1RM<br><br>Smith SSC hang high-pull with 30/40/50/60/70% 1RM | Males 30% 1RM<br><br>Females 30% 1RM, no SD across 30-50% 1RM<br><br>Males 30% 1RM, no SD across 30-40% 1RM<br><br>Females 40% 1RM, no SD across 40-50% 1RM<br><br>Males 40% 1RM, no SD across 30-60% 1RM<br><br>Females 40% 1RM, no SD across 30-60% 1RM |
| Turner et al. (2012) | Professional male rugby union players (n=11). 25.6±3.3 yr.      | Max: 1RM free weight squat<br><br>Power: free weight jump squat   | Free weight jump squat 20/40/60/80/100% 1RM  | 20% 1RM   |
| Zink et al. (2006)   | Recreationally weight trained males (n=12). 26.8±4.7 yr.        | Max: 1RM SSC free weight squat<br><br>Power: SSC free weight squat  | SSC free weight squat with 20/30/40/50/60/70/80/90% 1RM  | 40% 1RM, No SD across loads tested  |

Smith = smith machine, SSC = stretch shortening cycle, CO = concentric only, SD = significant difference

Training with the load that develops the highest power output is often referred to as  $P_{\max}$  training in the literature (Harris et al. 2008, Cronin and Sleivert 2005). Evidence exists to support the practice as an effective means of developing power; however, it is unclear whether it is the most effective practice. In a seminal study conducted by Kaneko et al. (1983) untrained males performed maximum effort repetitions on a resistance apparatus used to test the force-velocity relationship of the arm flexors. The participants were separated into four groups that each performed ten repetitions, three times a week for twelve weeks. The groups performed the actions with a resistance calibrated to 0, 30, 60 or 100% of the maximum force ( $\% F_{\max}$ ) that they could produce. In support of the paradigm of maximising the acute expression of a variable, isometric strength was best improved by those training with the 100% load, followed by 60, 30, and 0%  $F_{\max}$ . The order was reversed for the best improvements in peak velocity, and finally, the load that produced the greatest acute power values (30%  $F_{\max}$ ) resulted in the largest improvements in power. A similar pattern of results was reported by McBride et al. (2002) utilising the more complex jump squat exercise. The authors matched twenty six resistance trained males on the basis of their strength to mass ratio and assigned them to either a heavy resistance group that performed the jump squat with 80% 1RM, or a light resistance group focused on developing power with a load of 30% 1RM. The intervention duration was eight weeks, with pre and post measures of force, velocity and power recorded with the same resistances used in training. Those allocated to the light resistance group creating greater acute production of velocity and power, demonstrated significantly greater improvements in the variables over the training intervention, whereas the heavy resistance group demonstrated significantly greater increases in strength.

The studies conducted by Kaneko et al. (1983) and McBride et al. (2002) have been criticised for assuming that repetitions performed with 30% of maximum produces the greatest power values (Cronin and Sleivert 2005). As discussed above, research has established that the load that maximises acute expression of power is dependent upon a number of factors and it has been argued that their ability to support the superiority of  $P_{\max}$  training for developing power is therefore reduced. Only a limited number of studies have conducted training interventions that identify and subsequently adopt the load that maximises power for each participant. Newton et al. (2006) adopted this protocol with elite female volleyball players performing the jump squat. Over a four week period during the middle of the competitive season the training resulted in increases in force, velocity, power and returned vertical jump performance to its original values tested at the beginning of the season. The authors did not include control or comparison groups due to ethical issues

associated with the manipulation of elite athletes training regimes. As a result, the study provides support for the effectiveness of  $P_{max}$  as a training practice for elite athletes but fails to demonstrate superiority relative to other training practices. Wilson et al. (1993) compared the force and performance improvements of resistance trained males allocated to  $P_{max}$  training, training with moderate resistances (6-10 RM), or plyometric depth jumps. The groups trained two times per week for ten weeks with the  $P_{max}$  group recording the greatest increases in vertical jump height, sprint time and force production during fast velocity isokinetic actions. The authors concluded that the results provided strong support for the superiority of  $P_{max}$  training for improvements in tasks requiring high power outputs. Data reported by Harris et al. (2008) on elite rugby league players showed that  $P_{max}$  and heavy strength training resulted in similar performance improvements over a seven week period. Interestingly, despite obtaining increases in sprint speed, the athletes' pre to post force and power values decreased. The authors suggested that this may have been a transitory issue related to fatigue. However, the decreases in peak velocity and power were significantly less in the  $P_{max}$  group compared with the heavy resistance group.

Collectively, there is strong support for the effectiveness of training practices that maximise the acute expression of a given variable; in particular, substantial evidence has been obtained for the development of force and power. These findings have been extended to other mechanical variables such as RFD; however, despite the intuitive appeal of this approach and its feature as one of the main paradigms in the study and practice of strength and conditioning, research should continue to assess the validity of this approach for each variable demonstrated to impact upon sporting performance.

Dissemination of the methods used to measure biomechanical variables, combined with the availability of relatively inexpensive equipment (e.g. linear transducers and portable force platforms) has led many researchers to focus on the effects of small manipulations rather than comparing diverse training regimes. Examples of manipulations used in recent studies include the use of weightlifting shoes (Kimitake, Fortenbaugh and David 2012), the use of compressive garments (Eitner, LeFavi and Riemann 2011, Blatnik, Skinner and McBride 2012), the use of variable resistance material (Israetel et al. 2010, Baker and Newton 2009) and modifications to exercise technique (McBride et al. 2011, Drinkwater, Moore and Bird 2012). These results, and others from similar studies, are being used to provide information within the framework of maximising acute expression of variables, to assist strength and conditioning coaches with their training prescription. This PhD project uses a similar

approach to assess whether the training practices used by contemporary powerlifters have the potential to provide appropriate mechanical stimuli for athletes of other sports.

In summary, the use of biomechanics as a means to investigate and inform the practice of resistance training has developed over time. Initially, movement analysis approaches were used to observe, evaluate and recommend techniques used to perform resistance exercises. More recently, the variable based approach has been used to identify the most important kinematic and kinetic variables that influence performance in common sporting tasks. Once a particular variable has been identified, appropriate training practices can be selected on the basis of a central paradigm in strength and conditioning that asserts the most effective training regimes are those that maximise the acute production of the variable targeted. Whilst more research is required to fully substantiate the paradigm, there is clear evidence to support the use of the approach, in particular with regard to training aimed at the development of maximum strength and power. The major advantage of the paradigm is its ability to provide a bridge between researchers and practitioners. Much of the contemporary biomechanics research investigating resistance training is designed to assess the effect of manipulating an exercise on the mechanical stimulus created. Using this method, researchers can assess the effects of novel training practices and provide coaches with empirical data to inform their training prescription.

## 2.4 Summary

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The aim of this literature review was to provide background for the work conducted in this project and provide a clear rationale for the overall direction taken in this PhD. The initial sections of the review provided an introduction to resistance training and outlined the importance of models in designing programmes and conducting research. Additionally, evidence to support the use of resistance training as an effective means to improve sports performance was considered. Section two of the literature review introduced the concept of model training practices developed through trial and error by strength athletes. The relevance of each group was highlighted, with emphasis placed on the contemporary practices of powerlifters as a potential source of effective, novel training for other athletes. In the final sections of the review, much of the theoretical framework used to underpin this project was discussed. In particular, the variable based approach of biomechanics and the paradigm of maximising acute production of a target variable were linked to highlight a means of assessing training practices in the latter sections of the project.

## **CHAPTER 3. CONTEMPORARY TRAINING PRACTICES OF POWERLIFTERS**

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### **3.1 Prelude**

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Having defined the research question and completed the background work to the project, the next stage of the process sought to identify the contemporary training practices used by high-level powerlifters. Widespread proliferation of internet sites and online practitioner forums has increased dissemination of information regarding all forms of physical training. Information on resistance training practices appears to be amongst the most widely disseminated, due to interest from diverse populations who seek to improve strength, performance and body aesthetics. In parallel with the large increase in information available from lay sources, the number of research articles investigating resistance training practices has also increased substantially over the last two decades. An important feature of this newly available information has been to increase awareness of the extensive range of resistance training practices that exist. However, the large volume of information available and diverse topics covered presents a challenge when attempting to summarise the training practices of any particular group. In addition, commercial interests may lead to the distortion of the impact and prevalence of individual training practices in order to create additional revenue. Therefore, in order to identify the training practices used by powerlifters, data were collected from successful athletes currently competing by means of questionnaires and interviews.

## 3.2 Introduction

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Powerlifting is a popular strength sport that draws competitors from across the world and features in high profile sporting events such as the Commonwealth and World Games. Athletes are separated into categories based on age, body mass and gender to provide fair competition. Each athlete is given three attempts to lift the heaviest load possible in the squat, bench press and deadlift. The winner in each division is the individual who lifts the heaviest cumulative load across the three exercises. An overall winner within gender and age categories is determined by scaling the cumulative loads relative to each athlete's body mass using a non-linear scaling equation (Hester et al. 1990). The competition and training demands of powerlifting have been shown to develop a unique phenotype in sport. Successful powerlifters generally exhibit very large muscular girths and bony breadths, but display average limb lengths (Keogh et al. 2007, Bale and Williams 1987, Brechue and Abe 2002). In addition, mesomorphy (defined as musculoskeletal robustness in the somatotype schema of Heath and Carter (1967)) values reported for elite heavyweight powerlifters are amongst the highest reported in the scientific literature (Keogh et al. 2007). Research has also established that both successful male and female powerlifters exhibit similar anthropometric characteristics when scaled relative to height and mass (Keogh et al. 2007, Keogh et al. 2008). In combination with extensive changes in morphology, training for the sport of powerlifting has been shown to create substantial increases in physical performance. Elite lightweight powerlifters are able to lift over five times their body mass in the squat and deadlift, and over three times their body mass in the bench press (Keogh et al. 2007). Elite heavyweight powerlifters are unable to lift the same relative loads as lighter competitors due to the non-linear relationship between strength and mass (Jaric 2002); however, the absolute loads lifted by the heaviest athletes now exceed 570kg in the squat, 460kg in the deadlift, and 485kg in the bench press (Soong 2011).

Information from lay sources and official powerlifting records over the last decade highlight that performances are improving at a faster rate than at any previous time (Bates 2012, International Powerlifting federation 2012, Tate 2006). Whilst the reasons for these improvements are likely to be multi-factorial, it has been suggested that recent changes in training practices used by powerlifters is an important factor (Simmons 2007, Tate 2006). The internet, and in particular practitioner forums, have been used extensively over the last decade to disseminate training information to a worldwide population, with large online sites attracting over 60,000 daily visitors (StatShow 2011). Training information relating to

powerlifting is varied and ranges from the use of nutritional supplements to technical details of how to perform specific exercises. One of the most popular topics discussed on websites are the various training systems used and promoted by powerlifters. Training systems can be conceptualised as attempts to structure training by providing general principles that lead to related programs. These are distinct from training models (discussed in chapter two), where the objective is to provide an understanding of how to design and study programs for a wide range of training goals. Training systems used and promoted by powerlifters differ greatly in their complexity and output in terms of programs created (Kraemer and Fleck 2004). Traditionally, powerlifters have used relatively simple training systems which produced homogenous training programs. Popular examples included Bill Starr's 5x5 and Steven Korte's 3x3 systems which focus extensively on the use of the bench press, squat and deadlift (Purzel 2009). The use of more complex training systems, which provide greater variety, is believed to be the cause of recent changes in training practices and consequent improvements in performances (Tate 2006). Examples of more advanced training systems which are believed to be commonly used by novice and high-level powerlifters include the Westside barbell system and Jim Wendler's 5/3/1 system (Purzel 2009).

To the author's knowledge, there have been no longitudinal studies conducted to assess the effectiveness of different training systems used by powerlifters. The majority of studies investigating various resistance training regimes have focused on interventions recommended for the general public (American College of Sports Medicine 2009) or athletes competing in more traditional sports (e.g. American football, basketball and tennis) (Hoffman et al. 2004). There are, however, commonalities between resistance training interventions studied in the scientific literature, and fundamental aspects of training systems used traditionally by powerlifters. Bill Starr's 5x5 training system was one of the first adopted by powerlifters (Purzel 2009). Its main features include performance of the bench press, squat and deadlift on multiple sessions each week for five sets of five repetitions. The first four sets of each exercise are considered as a warm-up and feature sub-maximum ascending loads. The resistance for the final set of each exercise is selected so that completion of all five repetitions requires maximum effort. Once an individual is able to complete each set for five repetitions the loads are collectively increased for the next session. This progressive overload method is similar to that used in the first systematic training system pioneered by Delorme (1945). Multiple studies have confirmed that progressively increasing resistance upon achieving set targets can provide significant improvements in strength, particularly in novice trainees (Campos et al. 2002, Stone and

Coulter 1994) or those rehabilitating an injury (Delorme 1945, Lombardi et al. 2008, Fish et al. 2003). In addition, seminal research conducted by Berger (1962a) provides support for the use of resistances which allow a maximum of approximately six repetitions to provide effective increases in strength. However, more recent research suggests that the use of restricted loading schemes should be limited to novice athletes and that well trained individuals demonstrate greater increases in strength if a variety of resistances and repetition schemes are used (American College of Sports Medicine 2009, Peterson, Rhea and Alvar 2004, Fleck 1999). As a result, the Bill Starr 5x5 system is generally viewed as a strategy for beginner powerlifters and that more advanced systems are appropriate for individuals with greater training experience.

Training systems used frequently by intermediate powerlifters have generally incorporated basic periodization models, featuring sequential training blocks of 2 to 4 weeks in duration (Tate 2006). Variation in volume and intensity are programmed primarily between blocks and are structured to present a stimulus that first increases muscular endurance, then muscular hypertrophy and finally maximum strength. This organisational method of programming the training stimulus is commonly referred to as a linear or traditional periodization (Plisk and Stone 2003, Turner 2011). The majority of studies that have compared linear periodized models with resistance training featuring unstructured variation in parameters have reported superior improvements for periodized training (Stone et al. 2000, Willoughby 1993, Willoughby 1992, Stowers et al. 1983). In addition, research has demonstrated that traditional models of periodization can improve the strength of individuals with moderate resistance training experience (Rhea and Alderman 2004). As a result, it is expected that powerlifting systems which include sequential variation in training will be more effective than simpler systems and could be used successfully by beginners and intermediates.

The first complex training system to be developed by powerlifters and promoted world-wide was the Westside barbell system (Purzel 2009). Many subsequent training systems used by powerlifters have incorporated various aspects of this original design (Defranco 2012). The principal feature of the Westside barbell system is a periodization scheme that features significant variation within training blocks and attempts to develop multiple fitness variables simultaneously (Simmons 2007). In the scientific literature, periodization strategies of this type are frequently referred to as undulating models. The majority of recent research conducted on periodization has focused on comparing training programs created from either

linear or undulating models (Rhea et al. 2002, Monteiro et al. 2009, Buford et al. 2007, Alvar, Wenner and Dodd 2010, Jimenez and Paz 2011, Hartmann et al. 2009, Prestes et al. 2009). The results of these studies have been mixed, with some reporting greater increases in strength and power with undulating models (Monteiro et al. 2009, Rhea, Kenn and Dermody 2009) and others reporting no significant differences (Buford et al. 2007, Alvar, Wenner and Dodd 2010, Jimenez and Paz 2011, Hartmann et al. 2009, Prestes et al. 2009). Overall, it appears that undulating models may be more effective than their linear counterparts, depending on factors such as training experience, length of intervention and degree of variation within the programs. In the majority of studies that reported no significant differences between periodization strategies, general trends emerged indicating greater results were obtained for participants in non-linear groups (Buford et al. 2007, Alvar, Wenner and Dodd 2010, Prestes et al. 2009). The relatively small sample sizes and short training periods incorporated in the studies most likely explain the lack of statistical support.

It is important to note that the originators of the Westside Barbell system identify their periodization model as the conjugate method (Simmons 2007). This term was selected as it was believed to appropriately describe the process of simultaneously developing multiple fitness variables (Tate 2006). However, in the scientific literature the conjugate periodization model is defined as an advanced periodization strategy that utilises sequential targeting of fitness variables with periods of intentional overreaching, followed by periods of restoration (Plisk and Stone 2003). For the purposes of this work the periodization scheme utilised in the Westside barbell system will be deemed to be comparable to that of an undulating model.

Recent training systems developed by powerlifters are more recognisable for the novel training practices they incorporate rather than their organisational structure. Examples of novel training practices currently promoted by powerlifters include the use of resistive bands and chains, and weight releasing devices which are implemented to alter the magnitude of the resistance during an exercise (Simmons 1999, Simmons 1996). Other practices include the use of modified barbells, unconventional lifting implements and various sled dragging exercises which are popular with track sprinters (Tate 2006, Purzel 2009). Based on anecdotal reports of the effectiveness of these practices for developing maximum strength and power, large numbers of athletes and recreationally trained individuals have begun to perform them. This has led to initial research being conducted by sport scientists. A small number of studies have investigated the use of bands (Mcguigan, Wallace and Winchester

2006, Wallace and Winchester 2006), chains (Berning and Adams 2004, MCCURDY et al. 2009) and weight releasing devices (Doan et al. 2002, Ojasto and Hakkinen 2009) on exercise biomechanics, physiological responses and changes in performance. More recently, biomechanical and physiological research studies have investigated training with unconventional implements (McGill, McDermot and Fenwick 2009, Keogh et al. 2010). Collectively, results have indicated that the contemporary training practices used by powerlifters have the potential to create distinct biomechanical and physiological stimuli. However, research in the area requires a more systematic approach in order to further our understanding. The individual training practices investigated in previous studies have generally included restricted ranges for the experimental parameters and therefore lack ecological validity. In addition, scientific study generally lags behind the actual practices used by athletes in the field. The purpose of this descriptive study was to identify the contemporary training practices used by high-level powerlifters and to detail their motivations for employing such methods. The identified practices will be differentiated on the basis of their underlying mechanics and studied in the subsequent chapters.

### **3.3 Methods**

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#### **Approach to the problem**

To identify the contemporary training practices used by powerlifters and their motivations for use, questionnaires and semi-structured interviews were used. Questionnaires were completed by senior-level powerlifters from Scotland, England, Ireland and Wales at an international competition. Interviews were conducted at later dates using a sample of Scottish powerlifters from the same competition. Questions for both tools were created by first performing focused research of powerlifting practices reported in lay sources. The information obtained was used to develop primarily closed questions for the questionnaire and more open and flexible questions for the interview schedule.

#### **Participants**

The participants included the top fifteen ranked male Scottish powerlifters and seventeen additional international competitors invited to the 2007 Four Nations Championship held in Livingston, Scotland. The participants included multiple national, international and commonwealth champions and record holders in weight categories ranging from the under 75kg class to the unlimited weight class. Performance in powerlifting is measured by the Wilks equation which combines multiple power laws to scale the loads lifted by each individual relative to their body mass (Vanderburgh and Batterham 1999). Based on 2007 competition results the average Wilks score of the group was  $450.26 \pm 34.7$ , with previous research classifying high level international athletes as those with Wilks scores greater than 410 (Keogh et al. 2009). Each of the competitors participating in the international competition was invited to complete the questionnaire. Interviews were conducted in person and due to logistical constraints, only the Scottish powerlifters were invited to participate. The research design was approved by the Robert Gordon University Research Ethics Committee.

#### **Questionnaire**

A twenty-item questionnaire sectioned into six areas of inquiry (1. repetition speed; 2. explosive training load; 3. resistance materials used; 4. adjunct power training methods; 5. exercise selection; 6. training organisation) was created (Appendix I). Each section

represented an important aspect of contemporary training methods identified from research of lay material. Closed questions featured for all segments except for exercise selection where both closed and open questions were presented. The questionnaire was piloted with four local powerlifters with feedback specifically sought on language and content prior to its use on the participant population. Based on the feedback a few minor changes to the phrasing of three questions were made.

## **Interview**

Semi-structured interviews were conducted to provide more detailed information regarding the training practices used by high-level powerlifters and their motivations for adopting such practices. In combination with a brief interview schedule (Appendix II), detail-oriented probes with follow up questions were used to provide more accurate accounts (Patton 2002). The interviews were conducted according to the recommendations made by Kvale (1996) and lasted approximately 25 to 40 minutes depending on the participant's engagement with the process. Interviews were audio recorded and then transcribed verbatim.

## **Data Analysis**

Descriptive statistics were used to summarise the responses from questionnaires. Data collected from interviews were analysed inductively within a framework supported by the study aims. An inductive rather than deductive approach was used to ascertain the breadth of the training practices used. The collated raw data from interviews were organised into themes. This was achieved by the primary author (who was also the interviewer) reading and then re-reading the transcripts to become familiar with them. The interview transcripts were then split into "meaning units" with tags provided to represent single ideas expressed by the individual (Côté et al. 1993). A full list of tags created across the nine interviews was then analysed, with similar tags collapsed into categories (Côté et al. 1993). The important themes were then identified by sorting categories to ensure they were distinct, and finally, ensuring at least four of the nine athletes discussed elements of the theme during their interview to demonstrate group patterns.

## 3.4 Results

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### 3.4.1 Survey

Of the thirty two male powerlifters engaged in the competition a total of twenty eight (88%) completed the survey. Table 1 provides a summary of the results.

**Table 3.1:** Summary of item responses

| <b>Repetition Speed Heavy Loads (80-100% 1RM)</b>    | <b>% of powerlifters using the training practice</b> |
|--|--|
| Performed squat as fast as possible                  | 64.3%  |
| Performed bench press as fast as possible            | 60.7%  |
| Performed deadlift as fast as possible               | 64.3%  |
| <b>Repetition Speed Submaximal Loads (0-70% 1RM)</b> |  |
| Performed squat as fast as possible                  | 75.0%  |
| Performed bench press as fast as possible            | 67.9%  |
| Performed deadlift as fast as possible               | 75.0%  |
| <b>Explosive Training Load (0-70% 1RM)</b>           |  |
| Used 0-10% for speed repetitions                     | 0%   |
| Used 11-20% for speed repetitions                    | 0%   |
| Used 21-30% for speed repetitions                    | 0%   |
| Used 31-40% for speed repetitions                    | 3.6%   |
| Used 41-50% for speed repetitions                    | 39.3%  |
| Used 51-60% for speed repetitions                    | 39.3%  |
| Used 61-70% for speed repetitions                    | 53.6%  |
| <b>Resistance Material Used</b>                      |  |
| Used chains in training                              | 57.1%  |
| Used elastic bands in training                       | 60.7%  |
| <b>Adjunct Power Training Methods</b>                |  |
| Performed the clean in training                      | 60.7%  |

|  |       |
|--|-------|
| Performed the jerk in training               | 10.7% |
| Performed the snatch in training             | 14.3% |
| Performed pulls in training                  | 17.9% |
| Performed upper body plyometrics in training | 14.3% |
| Performed lower body plyometrics in training | 17.9% |
| <b>Exercise Selection</b>                    |       |
| Performed box squats in training             | 46.4% |
| Performed board press in training            | 57.1% |
| <b>Periodization</b>                         |       |
| Used periodization in training organisation  | 96.4% |

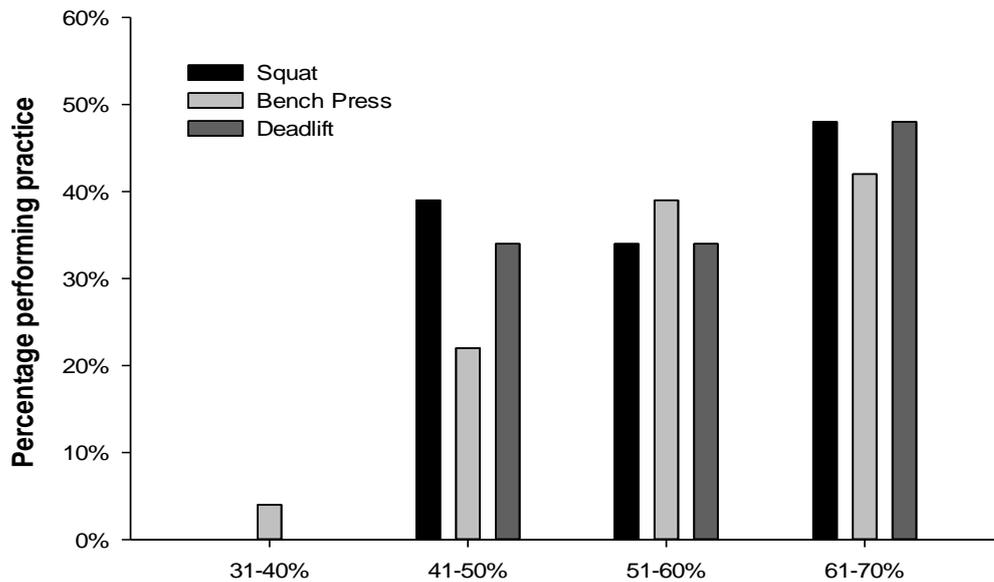
### **Repetition Speed**

Participants were asked if they performed their heavy sets (80-100% 1RM) in the squat, bench press and deadlift as fast as possible (maximum), or at controlled speeds (less than maximum). Thirteen of the twenty eight (46%) participants performed all three exercises as fast as possible and twenty two (79%) performed at least one of the exercises as fast as possible.

### **Explosive Training Loads**

Participants were asked if they attempted to lift sub-maximum loads (0-70% 1RM) as fast as possible in the squat, bench press or deadlift. The sub-maximum loads were presented to the participants in seven categories (0-10%, 11-20%, 21-30%, 31-40%, 41-50%, 51-60%, 61-70%) with instructions to select multiple categories if appropriate. The responses showed that the majority of the powerlifters (82%) performed the practice with at least one of the exercises, and in each instance used more than one loading category. None of the participants reported using loads less than or equal to 30% of their maximum for explosive training. Figure 3.1 illustrates the percentage of powerlifters that used the various sub-maximum loading categories for the squat, bench press and deadlift.

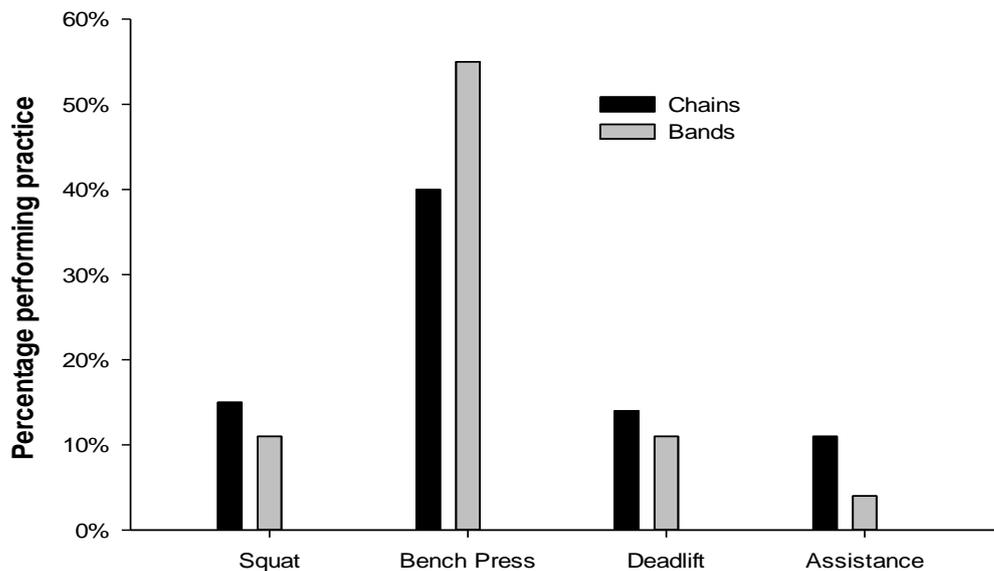
**Figure 3.1:** Analysis of sub-maximum loads used for speed repetitions in the squat, bench press and deadlift



### Resistance Materials Used

Thirty nine percent of the powerlifters surveyed incorporated elastic bands in their training and 57% reported using chains. Figure 3.2 illustrates that chains and bands were most commonly used with the bench press exercise.

**Figure 3.2:** Analysis of the use of chains and band with squat, bench press, deadlift or assistance exercises.



## **Adjunct Power Training Methods**

Sixty nine percent of the participants reported that they regularly performed the Olympic lifts or their derivatives (cleans, snatch, pulls, and the jerk) as part of their overall training regime. A minority of the participants also reported performing upper and lower body plyometric drills (14% and 18% respectively). In general, it was the same participants that performed the exercises for both the upper and lower body.

## **Exercise Selection**

Thirteen of the twenty eight (46%) participants performed the box squat in their training. Participants who included the box squat were asked to indicate how frequently they performed the lift in comparison to the free squat. Of those who performed the exercise, 46% reported performing the box squat less often than the free squat, 23% reported that they performed both lifts with the same frequency, and 30% reported performing the box squat more often than the free squat.

Participants were also asked which assistance exercise they felt best improved performance in the squat, bench press and deadlift. Box squats were cited most frequently for the squat (29%), close grip bench press was cited most frequently for the bench press (43%), and platform deadlifts were cited most frequently for the deadlift (29%). Additional exercises cited included board presses (21%), speed deadlifts (18%), and safety-bar squats (18%).

## **Training Organisation**

Twenty seven of the twenty eight (96%) participants reported that they included some method of periodization in their training organisation.

### **3.4.2 Interviews**

Of the fifteen powerlifters invited, nine volunteered to be interviewed. Analysis of the transcribed interviews identified five themes related to the athletes training practices and two themes relating to their motivations for adopting such practices. The identified themes included: 1) sources of information; 2) training systems; 3) specificity of strength; 4) developing power; 5) developing technique; 6) scientific underpinnings; 7) heuristics. These themes will be explored further in the discussion section of the chapter.

### **3.5 Discussion**

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Questionnaires and interviews employed in this study were used to obtain information on multiple aspects of the training practices of high-level powerlifters. Questionnaires were primarily used to determine whether successful powerlifters utilised novel training practices currently promoted through internet sites and practitioner forums. In contrast, interviews were used to obtain a more complete representation of the athletes' training and to determine their motivations for adopting each practice. The results from the questionnaires and interviews demonstrated substantial overlap, indicating the importance of novel training practices in the preparation of high-level powerlifters. The majority of the powerlifters surveyed reported using multiple training practices aimed at developing power and the ability to produce large forces over short time periods. In addition, responses to questionnaires revealed a wide range of exercises used by powerlifters, thereby illustrating the possible diversity in training programs. The development of power and the use of specific resistance exercises to enhance competition performance were the most frequently discussed themes during interviews. Other themes included the development of technique, the use of training systems and the importance of information sources to develop training practices. All athletes interviewed reported that they used trial and error to enhance the effectiveness of their training. In addition, the majority of those interviewed justified their use of various training practices on the basis of purported biomechanical or physiological advantages. The following sections discuss in detail the content of themes identified from interviews and relate the findings where appropriate to the questionnaire results and previous literature.

#### **Information sources**

Each of the athletes interviewed discussed the importance of obtaining current information to develop their training regimes and improve performance. A variety of information sources were identified, with eight of the nine athletes stating that their primary source was the internet. The most popular internet sites identified were practitioner forums which featured discussion boards where powerlifters could comment on issues related to the sport and upload training journals and videos for peer feedback. Four of the nine athletes identified other powerlifters and training partners as the next most important source of training information. Additional sources identified included powerlifting magazines and local strength and conditioning coaches. In the scientific literature there is a paucity of data regarding the information sources used by athletes to develop their training. This may be due to many

athletes, particularly those competing at high levels receiving their training regimes from coaches and strength and conditioning practitioners. Examples include the sport of Olympic weightlifting where coaches play an extensive role in the training design and competition management of their athletes (Fry and Newton 2002). In contrast, the majority of powerlifters compete individually and do not employ coaches. The relatively isolated nature of powerlifting may explain why resources on the internet are so popular and communal. Internet sites enable large numbers of individuals to assist each other and monitor the effectiveness of various training practices by reviewing the progress of online users. The communal nature and usefulness of online sites was expressed by one powerlifter who stated the following during interview –

“You get a lot of good people online... folk that know what they’re talking about and are strong. If you think about it, you’ve got some of the best powerlifters in the world putting up (their) training, putting up (their) videos and answering Joe Blogg’s questions.” (04)

### **Use of training systems**

The interviews also revealed that information sources used by powerlifters are closely related to the training systems they adopt. Almost all of the powerlifters surveyed reported that they adhered to long-term periodized programs. In addition, eight of the nine athletes interviewed stated that they develop the majority of their periodized programs through information and templates posted online. When designing a long-term periodized program there are a number of variables that have to be considered (Plisk and Stone 2003, Fleck 1999). Training systems provide a framework which assist in the development of long-term plans by constraining the number of variables that require manipulation. When those interviewed in the present study were asked to describe how they organise their training, five of the athletes stated that they adhered to a training system and two stated that they incorporated elements from a training system. All seven of these individuals stated that it was predominantly the Westside Barbell system that they incorporated based on information obtained from online sources. The athletes provided a number of reasons as to why they followed the Westside Barbell system, with multiple athletes citing factors such as variety in training, the frequent use of maximum resistances, predilection for novel training practices, and approval of results obtained –

“I like the four (training) days. I like the speed work, chains, bands, box squats... and it gets you strong.” (05)

“Lifting multiple 1RM’s each week really works. I rotate my max lifts every two weeks and that seems to keep my strength going up and up.” (06)

“I’ve tried (other programs including) Ed Coan’s, five times five, Russian volume, German volume, and Westside gives better gains. I don’t do all the template, but I do the heavy and speed days.” (08)

“I like Louie (Simmons), I’ve got his videos and online stuff. Everyone uses it (Westside Barbell System), so folk can help out and give advice.” (04)

“There’s not that many systems to use. Westside’s a bit mystical, but it’s based on science, and chains and bands are different. They work (bands and chains) and my squat is suited to the box (i.e. the box squat), so it’s all good for me.” (06)

As a result of the popularity of the Westside barbell training, a number of similar systems have been developed (Purzel 2009). In particular, attempts have been made to tailor the system to the training level and goals of the individual. Two of the athletes in the present study stated their belief that the Westside barbell system was most appropriate for powerlifters with substantial training experience. Similar opinions held by strength and conditioning coaches has led to the development of derivative training systems which are less demanding and believed to better suit less experienced powerlifters (Defranco 2012). In addition, training regimes that integrate features of the Westside barbell system with more general sports training have been developed to improve the physical conditioning of athletes other than powerlifters.

## Specificity of Strength

Powerlifting competitions are generally viewed as an accurate test of overall body strength (Siff 2003). The competition movements require activation of large amounts of muscle and enable individuals to produce forces at the maximum capacity of the human body (Gotshalk 1985). As a result, previous discussions of how powerlifters should train have emphasised the importance of developing the strength of individual muscles (Kraemer and Fleck 2004). However, during interviews for the present study, the majority of athletes stated that general increases in strength were of limited benefit to powerlifting performance and that optimal improvement in strength should target their individual weaknesses in the competition lifts. Moreover, many of those interviewed repeatedly used the term “specific-strength” when referring to the premise that not all increases in force capability would improve competition performance. Interestingly, only two of the athletes interviewed expressed the opinion that overall strength was the most important factor in determining performance. In both cases, the athletes competed in the heaviest weight category and their responses appeared to relate the concept of total muscle mass with overall strength and performance -

“Most important part of (power) lifting is strength. All lifts are set (limited) by the amount of muscle you got. You can try and squeeze out gains by messing with technique or changing your equipment, but how much you lift is how big you are”.  
(05)

“The strongest guys are the biggest guys. To deadlift 400 (kilograms), except for one or two freaks, you have to be 150 (kilograms) or heavier. It’s as simple as that.” (01)

Results from the survey and interviews revealed a large breadth of training practices used by powerlifters to enhance performance of the competition exercises. Many of these practices involved performing variations of the competition exercises to enhance transfer of adaptations. The survey revealed that the majority of the powerlifters altered the range of motion used to perform the competition exercises or added additional resistance material in the form of chains and bands. During interviews the athletes also discussed performing competition exercises with various modified barbells. For each of the training practices discussed, the athletes explained that they were used to target specific weaknesses in their competition performance –

“I’ve used chains cause they hit (stress) the top part of the lift. I can always get the bar off my chest or break it from the floor during deads (the deadlift), but I always struggle at lockout. The chains focus at the top and overload the joints.” (07)

“Chains and bands both increase my lifts, probably more so the bench (press). Bands are way tougher so when I take them off the weight feels really light and stable.” (02)

“The best exercise for improving deadlifts is rack pulls. Even though I usually fail at the bottom, the extra weight during the pull creates a much greater overload, plus it teaches you to stay rigid and tight.” (03)

“I find the trap bar and McKenzine bar to be a good switch-up from the straight bar. If you do a long cycle with any of them and come back to the straight (bar) your numbers always go up because your using heavier weights for the same lift.” (01)

A small number of previous studies have investigated the effects of modifying resistance exercises using methods similar to that described by the powerlifters. In his popular resistance training textbook, ‘Science and Practice of Strength Training’, Zatsiorsky (1995) categorised partial range of motion training as an advanced strength-training method. The author stated that performing exercises with a partial range of motion allowed individuals to train with loads greater than their 1RM and therefore create a strong stimulus to promote strength increases (Zatsiorsky 1995). The premise of this training method is based on the observation that the relationship between force transmission and resistance caused by the external load varies throughout an exercise (Mookerjee and Ratamess 1999). Probable mechanisms for variation in force transmission include the muscle length-tension relationship and changes in muscle activation and moment arm length of the musculotendinous unit (Zajac and Gordon 1989). Biomechanical research has previously established that, for exercises performed with maximum resistance, a “sticking region” exists where the balance between force transmission and resistance causes the velocity of movement to substantially decrease and in many instances reach zero (McLaughlin and Madsen 1984). The sticking region therefore limits the amount of resistance that can be

overcome by acting as the weakest link. Cross sectional research conducted on the bench press has shown that significantly heavier loads can be overcome if the range of motion (ROM) is decreased to avoid the sticking region (Mookerjee and Ratamess 1999, Clark, Bryant and Humphries 2008). However, longitudinal research comparing training interventions incorporating either full ROM or partial ROM repetitions has shown similar improvements in strength with both methods (Massey et al. 2004, Clark et al. 2011), or greater improvements when performing full ROM repetitions (Massey et al. 2005). The results obtained in longitudinal studies may reflect a trade-off in the overall mechanical and physiological stimuli created with each method. Whilst partial ROM training results in greater peak forces, full ROM repetitions require longer contraction times and produce more mechanical work (Clark, Bryant and Humphries 2008). Therefore, full ROM repetitions are more likely to stimulate a greater metabolic and hormonal response (Crewther et al. 2006). In addition, it has also been suggested that individuals without substantial resistance training experience may be unable to benefit from partial ROM training as the necessary neural adaptations to overcome supramaximal loads and fully augment the mechanical stimulus have not been created (Massey et al. 2005). Due primarily to the limited amount of research conducted, it is unclear how effective partial ROM training is for competitive powerlifters.

Altering the magnitude of the resistance during an exercise provides an alternative method to overcome the sticking region. When using resistance training machines this is easily achieved through the use of motors and cams. However, transfer of adaptations to sporting performance is believed to be limited when using resistance training machines in comparison to free-weight exercises (Frost, Cronin and Newton 2010). Recently, powerlifters have promoted a method of varying the magnitude of resistance during free-weight exercises by attaching additional resistance material in the form of bands and chains. During performance of the exercise the resistance is at its lowest during the initial stages of the movement where force capabilities of the body are generally low (Baker and Newton 2009). As the load is displaced upwards the bands stretch (or more links of the chain add to the barbell) to increase the overall resistance and match the enhanced force capabilities of the body. In contrast to partial ROM training, the addition of bands and chains allow full repetitions to be performed and therefore may provide a more effective combined mechanical and physiological stimulus. In addition, some strength and conditioning coaches have suggested that the addition of bands and chains has the potential to enhance core stability and neurological adaptations to strength training (Berning, Coker and Briggs 2008). However, the majority of training related claims regarding bands and chains are anecdotal,

and despite widespread popularity of the training practice, research in the area is still limited.

Many of the studies investigating the use of bands and chains are of a cross-sectional design and have sought to measure the effects of including the resistance material on mechanical parameters believed to be important in stimulating adaptations. The total resistance added when using bands and chains is likely to determine whether appropriate changes to the mechanical stimulus are created. Over half the powerlifters surveyed in the present study reported that they regularly used either bands or chains in their training. Of the nine powerlifters interviewed, seven confirmed that they used either bands or chains as part of their training preparation. When asked to detail how they incorporated the resistance material within their training, it was consistently remarked that the bands and chains had to represent a large percentage of the overall resistance to be effective. Three of the powerlifters stated that they regularly incorporated chain and band resistances of approximately 40 to 60% of their 1RM lift. Resistances approaching these magnitudes have not been investigated in previous research. In multiple studies the resistance added through chains and bands has been as low as 5% of the participant's maximum strength (Ebben and Jensen 2002, Baker and Newton 2009, Berning, Coker and Briggs 2008, Coker, Berning and Briggs 2006, Anderson, Sforzo and Sigg 2008). Therefore, further research is required to investigate the mechanical effects of the materials with loads commonly used in practice.

The use of modified barbells is a training practice commonly associated with the Westside Barbell training system. Of the nine athletes interviewed in the present study, five stated that they regularly used modified barbells to target specific weaknesses in their competition lifts, or to provide variation in their training. It was further identified that modified barbells were most commonly used to perform the deadlift and squat. To the author's knowledge, only one previous study has investigated potential changes in exercise biomechanics when using a modified barbell. Lander et al. (1986) compared joint kinematics and kinetics of six experienced male weightlifters performing the squat with a regular barbell or a modified barbell that could be adjusted to progressively lower the vertical height of the external resistance. A 5RM load was selected with the resistance lowered by 18 and 36% of the participant's height. The results showed no significant differences in joint kinematics and kinetics across conditions. Indirect assessment of the stress placed on the lumbar spine was obtained by measuring intra-abdominal pressure (IAP). The results demonstrated that

IAP was significantly lower during squats performed with the regular barbell. The authors interpreted this finding as evidence of reduced stress on the lumbar spine when squatting with the modified barbell. Joint moment data were collected at the hip and not the lumbar spine and therefore the authors' conclusions are difficult to confirm. The relative role of IAP on spinal mechanics remains controversial; however, recent models do suggest that increased IAP provides a mechanism to increase stiffness of the spine, and thereby indicate greater stresses experienced (Arzadeh et al. 2012). Despite the apparent popularity of modified barbells among powerlifters, there is at present limited information to assess their potential effectiveness.

### **Developing power**

Seminal research conducted by Garhammer and McLaughlin (1980) demonstrated that power production during maximum resistance squats, bench presses and deadlifts was considerably lower than that produced during Olympic weightlifting exercises. As a result of the findings, the majority of researchers and strength and conditioning coaches concluded that power development was not an important training requirement for the sport of powerlifting. Until the proliferation of the Westside Barbell system, the majority of powerlifters adhered to training programs which focused on developing force production capabilities during low velocity movements. However, one of the main features of the Westside barbell system, in addition to the use of heavy resistances, is the training practice of lifting sub-maximum loads as fast as possible (Simmons 2007). The rationale for the training practice is based on the theory that overcoming sub-maximum loads at fast velocities generates significant muscular strain and provides a stimulus to enhance muscular power (Simmons 2007, Zatsiorsky 1995). In the Westside Barbell system the training practice is commonly referred to as the dynamic effort method or speed repetitions. Proponents of the system currently recommend that the dynamic effort method be performed with the bench press, squat and deadlift using loads between 40 to 75% 1RM (Simmons 2007). The survey conducted in the present study confirmed the popularity of the training practice amongst high-level powerlifters. Three quarters of those surveyed reported that they regularly performed maximum velocity repetitions in training. A small number of athletes reported using loads as light as 30 to 40% 1RM, with the majority reporting use of loads between 60 to 70% 1RM. Despite the popularity of the practice, it has not clearly been established how powerlifting performance is consequently improved. It has been suggested that the training practice can enhance maximum strength as well as muscular power (Simmons 2007). In addition, others have proposed that improvements in power may

increase 1RM performance by enabling individuals to impart more momentum to the barbell during the initial stages of the movement, and therefore progress through the sticking region (Mangine et al. 2008). Of the nine athletes interviewed for the present study, six stated that power was an important factor in their competitive performance. When these athletes were asked to explain why they thought power was important, all responses supported the rationales previously stated.

The following excerpts are from two athletes who emphasised the ability of power training to directly improve maximum strength -

“Power and strength are pretty much the same thing. If you keep upping the load with speed reps then you up your max load as well.” (09)

“I find power training, plyo’s (plyometric exercises), good for my max. Speed box squats are my best lift for squat. . . bench throws are also good for one rep bench press.” (03)

The potential for power training to improve 1RM performance by altering the kinematics of the movement is reflected in the following statements collected during interview –

“Power training helps you get out of the hole in the squat and gives you that first pop off the chest in bench (press).” (05)

“The (power) training is as important as strength training. If you watch the top guys lift - they don’t lift slowly, even the heavy weights fly up. . . the power type training is what lets you blast through a lift.” (06)

The hypothesis that maximum strength can be improved whilst participating in training designed to enhance muscular power has support in the scientific literature. Numerous studies investigating the physiological adaptations obtained from power training have reported increases in maximum strength over relatively short training periods (Harris et al.

2008, McBride et al. 2002, Moss, Refsnes and Abildgaard 1997, Cormie, McGuigan and Newton 2010a). However, the same research has demonstrated that increases in strength during power training are not as large as those achieved during traditional heavy resistance training (Harris et al. 2008, McBride et al. 2002, Moss, Refsnes and Abildgaard 1997, Cormie, McGuigan and Newton 2010a). A smaller number of studies have investigated the effects of combining heavy resistance training with power training (Lyttle, Wilson and Ostrowski 1996, Harris, Stone and OBryant 2000, Mangine et al. 2008). Results have shown that superior improvements in strength can be achieved when combining training methods in comparison with performing either method in isolation (Harris, Stone and OBryant 2000, Mangine et al. 2008). Mangine et al. (2008) compared strength increases obtained during a standard resistance training intervention and a training regime which combined heavy and sub-maximum resistances performed as fast as possible in a single session. The group combining training practices experienced significantly greater improvements in 1RM bench press scores than those performing the standard heavy resistances in isolation (11.6 vs. 7.1%). The authors suggested that improved results may have been achieved through greater neural activation accrued when combining methodologies or the addition of power training may have caused adjunct positive adaptations such as improved energy storage and release in tendons (Mangine et al. 2008). Further research is required to elucidate the mechanisms that may result in augmented strength improvements when combining training methodologies. In addition, research into how best to combine strength and power training to maximise improvements is also required.

Less evidence is available to support the hypothesis that 1RM performance can be improved by manipulating the kinematics of the exercise near the sticking region. Previous research has shown it may be possible to alter the position of the sticking region through changes in the movement strategy used to perform an exercise. McGuigan (1996) and Fernando (1989) both reported that the sticking region in the deadlift exercise occurs during the first half of the concentric phase when using a standard lifting technique. In contrast, the sticking region occurred more frequently during the second half of the concentric phase when using the sumo lift technique (McGuigan and Wilson 1996, Fernando 1989). Differences in position of the sticking region were most likely caused by changes in body posture and concomitant alterations to the relative positioning of the external resistance and internal muscle moment arms and length-tension relationships (McGuigan and Wilson 1996, Escamilla et al. 2000). It is important to note that, despite substantial differences in body postures adopted between techniques, the position of the sticking region remained unaltered for many athletes (Escamilla et al. 2000). This result demonstrates the difficulty in

overcoming the disparity between internal and external torque production to alter performance of a maximum lift.

Whilst there is no direct evidence that power training may alter the sticking region of an exercise, it should be realised that the majority of powerlifters take part in competitions where legal performance-enhancing equipment are used (Silver, Fortenbaugh and Williams 2009). Examples include the use of knee wraps and form-fitting garments made from dense mixtures of cotton and polyester. An ergogenic effect is obtained as the garments are stretched during the eccentric phase and then return the stored energy during the concentric phase (Silver, Fortenbaugh and Williams 2009, Harman and Frykman 1990). The elastic recoil is greatest during the initial phase of the concentric movement prior to the sticking region. It is believed that power training is more likely to improve 1RM performance when it is combined with performance-enhancement equipment (Tate 2006). The proposed mechanism is that power training increases the velocity of the exercise, which, when combined with the elastic recoil creates substantial momentum to assist in completing the movement. This mechanism was described by one of the powerlifters in the present study –

“When you wear a shirt the sticking point happens much closer to lockout. Speed benching is all about getting a big pop off the chest so that you max with the shirt to build speed and get straight to lockout.” (05)

Additional research investigating the effect of power training on the kinematics of heavy resistance exercises with and without performance-enhancement equipment is required to enhance understanding of the potential mechanisms of improvement.

### **Developing Technique**

A large section of contemporary information regarding powerlifting training is devoted to optimising technique in the squat, bench press and deadlift. For each exercise a number of key technique points have been proposed to create a favourable balance between the external resistance and the internal force production capabilities of the body. Research conducted by McLaughlin et al. (1977) on lifting techniques used by powerlifters during competition revealed a number of kinematic differences in the squat exercise between top

tier athletes and those producing lesser performances. The results showed that the best powerlifters maintained a more upright posture and exhibited greater restriction in anterior displacement of the knee. Similar research conducted by Escamilla et al. (2001) on the deadlift also identified kinematic differences between athletes of various levels. Within each weight category the athletes producing the best performances exhibited greater knee flexion at lift-off, and positioned the barbell closer to the body throughout the exercise (Escamilla et al. 2001). The majority of lay material regarding technique in powerlifting has focused on the bench press and squat. A large amount of information has been developed for the bench press due to substantial improvements in performance which can be obtained when using ergogenic equipment. Form-fitting shirts have been shown to substantially increase performance of heavy weight male athletes depending upon the stiffness of the material and skill of the individual (Bates 2012). Technique advice on the bench press has largely focused on minimising the vertical displacement of the barbell and maximising the elastic recoil from the shirt. The majority of athletes interviewed agreed that performance in the bench press was greatly affected by the use of ergogenic equipment and that specific training to optimise technique was required –

“I can get an extra 40kg with my shirt and that’s with using single ply only (not the stiffest material). One of my training partners can get almost 60kg out of the same shirt. For me, the trick is getting it on tight so I hit the centre of the chest plate.” (09)

“I hate using shirts, they’re so uncomfortable and horrible to get on. But, you have to use them. I go from about 200 (kg) without, to on a good day, 240 (kg), 245 (kg) with.” (01)

“Most of my reading tells you to squeeze your shoulder blades together, tuck your elbows, blow out and bench to the top of your belly and pull the bar apart on the way up. I need to flare my elbows at the top to lockout heavy loads.” (06)

“I use a really wide grip and force my back into the bench so the shirt doesn’t move when I’m benching. Also, you have to keep your head down, as soon as your head

rises the shirt moves up. Tuck my elbows on the way down and arch my back to stretch the shirt and explode as fast as possible on the way up.” (04)

Due to the specialist technique and equipment required to perform successful competition bench presses, it is unlikely that the exercise will transfer improvements to more general sporting actions. As a result, the exercise has received minimal attention from the wider strength and conditioning community. In contrast, researchers have investigated the effect of technique alterations on the stimulus created during the squat, which is commonly regarded as one of the best resistance exercises for developing athleticism (Donnelly, Berg and Fiske 2006, Hales, Johnson and Johnson 2009, Paoli, Marcolin and Petrone 2009). Initial research investigating different squat techniques used by powerlifters and Olympic weightlifters revealed that the powerlifting group positioned the barbell lower on their back and emphasised loading of the hip joint by restricting anterior displacement of the knee (Wretenberg, Feng and Arborelius 1996). The majority of recent technical advice developed for powerlifters performing the squat recommends that athletes should adopt a wide stance and attempt to maintain a vertical shin position throughout the lift (Simmons 2007, Tate 2006). These recommendations were made to further emphasise loading of the hip and lower back. Some practitioners have suggested that these recommendations will cause the mechanics of the exercise to reflect that of the deadlift. This could prove advantageous for powerlifters as adaptations would potentially improve both squat and deadlift performance if there were a close mechanical relationship between the exercises (Tate 2006). However, research thus far has been unable to demonstrate similar kinematic profiles between competition squats and deadlifts (Hales, Johnson and Johnson 2009). In order to perform the squat as is currently recommended by powerlifters, individuals may require considerable technical skill and training experience. To develop proficiency in the movement it has been recommended that individuals perform the box squat in training (Simmons 2007). This variation includes a small box placed behind the lower leg and requires the performer to descend to the box, momentarily pause, and then return to the starting position. The box enables the performer to maximise posterior displacement of the hip and maintain a vertical shin position by acting as a safety device to catch the individual if the COM is moved behind the base of support. Almost half of the powerlifters surveyed in the present study reported performing the box squat regularly in training. In addition, the exercise was cited most often as the best assistance exercise to improve squatting performance.

During interviews it became apparent the powerlifters' motives for performing the box squat were varied. Some confirmed that they used the exercise primarily as a means to improve their squatting technique, whilst others stated that they used the exercise to increase the strength of specific muscles or to improve their performance during the bottom portion of the movement where the sticking region occurs. Currently, the effectiveness of the box squat is promoted by numerous elite powerlifters and appears to be popular with athletes from a wide variety of sports. However, research investigating the biomechanical and physiological stimulus presented by the exercise is limited. McBride et al. (2010) compared kinetic and EMG data obtained from powerlifters performing the traditional squat and box squat. The authors reported only minimal differences in peak VGRF and muscle activity measured at the thigh. The experimental protocol utilised by McBride et al. (2010) did not calculate joint specific data or provide kinematic information regarding the movement strategies used by the powerlifters to perform each exercise. Due to the limited information currently available, coaches and athletes are unable to make informed judgements regarding the potential strengths and weaknesses of the box squat.

### **Scientific Underpinnings**

The early training regimes employed by strength athletes were developed largely on the basis of trial and error (Fry and Newton 2002). The first group of strength athletes to utilise systematic research to inform their training regimes were Olympic weightlifters. In the 1970s the Soviet Union and other Eastern European countries began to conduct scientific research into various aspects relating to the performance of Olympic weightlifting (Fry and Newton 2002). In 1986, the well known work of R.A. Roman (The training of the weightlifter) was published. The manuscript included detailed kinematic information of weightlifting exercises, acute training strategies, and multi-year planning schedules (Roman 1986). However, the use of systematic research to inform training practices did not spread to strength athletes from other disciplines due to their limited coaching and support structures. Only recently has the training material disseminated for powerlifters included reference to physiological or biomechanical research. In addition, the majority of this information is disseminated through non-peer reviewed internet sources. During interviews carried out for this study, when asked to explain their motives for performing different training practices, the majority of powerlifters referred to various neurophysiological or biomechanical concepts. When discussing the importance of performing repetitions as fast as possible multiple powerlifters stated that the practice was important to enhance the ability to "recruit more muscle fibres". In addition, the majority of those interviewed discussed the concept of

momentum with regards to high velocity repetitions and ultimately traversing the sticking region during maximum lifts. When discussing specific exercises or the use of modified barbells and variable resistance material such as chains and bands the majority of those interviewed provided mechanical rationales -

“Jump stretch bands and chains give you the same increase in resistance as you go up, but the stiffness of the jump stretch bands gives you a much steeper increase in resistance. So to get to lockout you have to create a lot of momentum.” (04)

“When you do the box squat it makes you swing the hips right back so you end up with your upper half bent over which creates massive torque at the back but like none at the knee. Big difference with the Olympic squat where your feet are close and you end up stressing the knees even though the weight is half as much.” (09)

“They’re a pain to get a hold of but speciality barbells are the best for targeting specific muscles and staying specific. My favourite is the safety squat bar, when you put the arms up you can sit far back and keep the head up, using your hips. Plus, the safety bar is a bit higher on neck so it makes it even harder for your hams (hamstrings) and lower back. My training partner always wants to do trap bar deadlifts instead of conventional or sumo. They’re not the best for me, but you lift a lot more weight and Eric Cressey talks a lot about how the angle shares the load between legs and there is less torque at the back for injury.” (05)

A cursory review of the many training articles disseminated for powerlifters in the lay material reveals that a growing number of authors are degree educated and use in-text citations to support their claims where possible. This growing trend appears to have influenced the training and understanding of powerlifters and may provide an effective bridge between researchers and practitioners. However, as these articles are not subjected to a rigorous peer-review process, there is potential for misinformation to be published.

## Heuristics

In combination with the desire to select training practices that are based on clear physiological and biomechanical rationales, the powerlifters interviewed in the present study all emphasised the need to adopt a trial-and-error approach to determine effectiveness. The majority of those interviewed distinguished between effectiveness of a given training practice for them personally and the potential utility for others. The concept of individuality and the athlete's specific needs based upon their phenotype, strength of different regions of the body, and lifting technique was expressed frequently during interviews -

"I don't have the flexibility in my hips or the hamstring strength to squat ultra-wide like a Chuck Vogelpohl (famous powerlifter). For some people it's effortless and they only look like they are squatting down half as much as I have to, but I tried it and it just does not work... not at all." (07)

"Tried doing the wave that Westside Barbell uses with the bench press. But after like 8 weeks it just wasn't doing anything for me. I found that I respond much better to heavy speed benches, keep the same load for 8 weeks then drop the exercise for 4 to 6 weeks and then back again but with the weight upped." (04)

"I have to cut a load of the stuff out. It all works for Jamie (training partner) but a lot of it, if anything makes me worse. I need to keep up a high volume of accessory work to keep size. Box squats and bands help because I have got long arms and weak legs so I always fail at top deadlift and right at hole in the squat. All the tricks for my bench do jack (nothing). I pretty much train like a bodybuilder for my bench and hit singles, doubles and shirt work closer to comps (competition)." (09)

The statements made by those interviewed are in accord with researchers who suggest that the optimisation of training requires both experienced based learning and research driven inquiry. For some contemporary training methods, flexibility to alter the training stimulus based on feedback is an integral feature (Siff 2003, Mann et al. 2010). An example includes the autoregulation method that enables athletes and coaches to adjust the content and structure of training to correspond with the performers physiological status on a day-to-day and week-to-week basis (Mann et al. 2010) Research has shown that adapting training to coincide with a performers current level of preparedness can produce superior results than

those obtained with traditional training interventions comprising fixed training sessions set weeks in advance (Mann et al. 2010). However, training methods which incorporate flexibility to adjust training sessions tend to do so with a restricted number of training parameters. In many instances training sessions are still pre-programmed, but variables such as the number of sets or repetitions are altered in attempts to match the training load with the athlete's current physiological status. Future development of training methods may seek to include periodic review of an individual's progress and alter more fundamental aspects of the training regime if warranted. This could prove difficult for certain sports where annual periodized plans are restricted by lengthy competition periods. However, in sports such as powerlifting where athletes have extended periods of time to prepare for competition the process of periodic review and potential restructuring may be beneficial.

### 3.6 Summary and Conclusion

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The results from the questionnaires and interviews conducted in this study demonstrate that the descriptions of the training methods used by powerlifters in the scientific research are no longer representative. Instead, high-level powerlifters study and subsequently implement many of the novel practices currently promoted through popular online sources. At present, one particular training system appears to be very influential with both lower- and higher-level powerlifters. The practices incorporated within this system are wide and varied, but most are designed primarily to influence the mechanical stimulus of associated exercises. This observation corresponds well with the research aims of this PhD project, which is to present a detailed analysis of the biomechanical stimulus of contemporary training practices used by powerlifters, and to assess their potential efficacy with general athletes.

Whilst it is clear that any attempt to categorise the principal mechanical features of the contemporary training practices identified in this chapter is to some degree arbitrary, for the purposes of this project such a process was required to proceed in a logical manner. The training practices identified were considered to fall into one of four categories, including: (1) Speed of movement; (2) Alterations to the external resistance; (3) Movement strategy; and (4) Use of ergogenic equipment. The first category represented the training practice of performing maximum velocity repetitions with traditional resistance exercises. The second category included the use of variable resistance material (bands and chains), and unconventional barbells that were designed to create changes in the resistance by altering the position of the load. The third category included movement techniques developed by powerlifters to maximise performance in the competitive lifts. The final category included the use of ergogenic clothing with supramaximal resistances. However, as the ergogenic clothing worn by powerlifters was considered unlikely to confer any direct or indirect advantages to general athletes, it was determined that this category did not correspond with the full set of research aims and therefore was not selected for analysis. Instead, the practices listed in the first three categories were considered to be representative of much of the contemporary training practices used by powerlifters and regarded as appropriate for study in the subsequent chapters.

## CHAPTER 4. IDENTIFICATION OF PERFORMANCE VARIABLES

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### 4.1 Prelude

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Human movement is a complex phenomenon that can be viewed from diverse physical, psychological and sociological perspectives. Perhaps the most commonly used perspective to study human movement comes from the field of mechanics. When applied to sport, mechanical analyses of movement characteristics used by performers to complete specific tasks are frequently reduced to the collection of a small number of variables, including position, force and time. However, the complexity of the human body and multitude of mathematical procedures that can be applied to these variables ultimately creates a large number of parameters that provide different information. At present, it is not fully understood which mechanical parameters are most closely related to the ability to successfully perform various sporting tasks. Greater understanding of these relationships should enable athletes and coaches to make more informed decisions when designing or selecting training regimes to improve performance. It is the purpose of this chapter to expand on previous research investigating the relationships between performance and single mechanical parameters, by employing regression analyses to develop predictor models that combine multiple factors. The results will be used to select the mechanical parameters measured in subsequent chapters to assess whether the powerlifting practices studied in this project could provide appropriate mechanical stimuli for general athletes.

## 4.2 Introduction

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The ability to effectively sprint, jump and change direction is believed to impact substantially on success in a wide variety of sports (Hori et al. 2008, Fry and Kraemer 1991, Cronin and Hansen 2005). As a result, numerous studies have sought to identify the factors that determine these abilities, with a view to developing more effective training programs (Hori et al. 2008, Wisloff et al. 2004, Peterson, Alvar and Rhea 2006, Baker and Nance 1999). Previous studies have typically used correlation analyses to identify associations between biomechanical variables and athletic tests that provide a measure of performance. Most frequently, popular resistance exercises such as the squat (Baker and Nance 1999, Chelley et al. 2010, McBride et al. 2009), jump squat (Sleivert and Taingahue 2004, Baker and Nance 1999) and clean (Hori et al. 2008, Baker and Nance 1999, Carlock et al. 2004) have been used to collect the input data. Of all the variables that have been studied, the relationship between maximum strength and athletic performance has been investigated most often using data collected primarily from 1RM squat tests. Based on a study of elite soccer players, Wisloff et al. (2004) reported correlations of -0.71, 0.78 and -0.68 between absolute 1RM values and 30 m sprint time, vertical jump height and 10 m shuttle time, respectively. Peterson et al. (2006) obtained slightly higher correlations for similar measures of performance with a more heterogeneous group of male and female college athletes, reporting correlations between 0.78 and 0.92. Research has also demonstrated that the relationship between maximum strength and measures of athletic performance may be improved if strength values are normalised relative to body mass (Peterson, Alvar and Rhea 2006, McBride et al. 2009).

Based on the belief that muscular power is a key factor for performance in many athletic tasks (Cronin and Sleivert 2005), a large number of correlation studies have measured biomechanical variables during explosive resistance exercises performed with sub-maximum loads (Hori et al. 2008, Kawamori et al. 2005, Sleivert and Taingahue 2004, Baker and Nance 1999). Many of these studies have also attempted to correlate measures of performance with variables such as velocity, impulse and RFD. A range of moderate to strong correlations have been reported depending on factors such as exercise selection, methods used to calculate the biomechanical variables and the sample investigated (Cronin and Sleivert 2005). Hori et al. (Hori et al. 2008) measured power production during performance of a jump squat with an absolute load of 40kg in a group of Australian Rules

football players. The results showed positive relationships with performance in sprinting, jumping and quick changes of direction ( $r = 0.49, 0.54$  and  $0.39$ , respectively). Baker and Nance (1999) also reported similar correlation values between power and sprinting ability in rugby league players, but only after power values were normalised relative to body mass (correlation improved from  $0.02$  to  $0.57$ ). In general, performance correlations with variables collected during explosive resistance exercises performed with sub-maximum loads have not been as large as those established for maximum strength measures.

It has been suggested that a preoccupation with correlation studies has limited understanding of the best predictors of important sporting tasks (Cronin and Sleivert 2005). Importantly, correlation studies only consider the isolated effect of single predictor variables, whereas performance in sporting tasks may be better explained by combining multiple variables. Instead, It has been recommended that future studies should adopt regression approaches to produce predictor models that combine anthropometric and biomechanical variables, as it is likely that both phenotypic and force related capabilities impact on performance (Cronin and Sleivert 2005). In comparison to a correlation analysis, multiple regression has the advantage of increasing the explanatory power of a given model whilst providing information to determine which variables contribute to the prediction and conversely, those that do not (Vincent 1994). There have been previous investigations that have incorporated strength (Blazevich and Jenkins 1998) or anthropometric variables (Davis et al. 2004) with a multiple regression approach to predict performance of common sporting tasks; however, to the author's knowledge, there have been no studies that have included both sets of information in combination with variables believed to reflect important features of the force-velocity and force-time curves. Therefore, the purpose of this study was to expand on previous investigations and identify which combination of anthropometric and biomechanical variables could best explain performance in sprinting, jumping and change of direction tasks in well-trained athletes. As previous research has identified exercise type and load to be important in influencing the production of biomechanical variables (Cormie et al. 2007), data were collected using multiple exercises over a range of external resistances.

### 4.3 Methods

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A regression based approach was used to obtain predictor models of performance in common sporting tasks. Predictor models included anthropometric data and biomechanical measures collected during resistance exercises performed with maximum and sub-maximum loads. The participants ability to sprint, jump and change direction were measured to represent performance. Testing was conducted on three separate occasions, with a minimum of forty-eight hours between each testing occasion to minimise the likelihood of fatigue. On day one, participants performed sprint and change of direction tests in an indoor gymnasium. On day two, participants performed maximum strength tests and were assessed for anthropometric characteristics using a 3D body scanner (Hamamatsu Photonics Model: BLM9036, Japan). On the final day of testing participants reported to the human performance laboratory to complete vertical jump tests and perform explosive resistance exercises with sub-maximum loads.

#### **Participants**

Thirty well-trained non-professional male rugby union players (age:  $24.2 \pm 3.9$ yr; stature:  $182.4 \pm 6.7$  cm; mass:  $94.1 \pm 12.3$  kg; resistance training experience:  $7.3 \pm 2.1$  yr) volunteered to participate in this study. Participants were recruited from a single team competing in the Scottish Rugby Union Premier League. Each of the athletes regularly performed explosive and maximum resistance exercises as part of their strength and conditioning regime. In addition, the athletes regularly performed sprint, vertical jump, and change of direction tests as part of their ongoing physical assessment. The study was conducted six weeks into the athletes preseason training after a de-load micro-cycle. Participants were notified about the potential risks involved and gave their written informed consent to be included. Prior approval was given by the ethical review panel at Robert Gordon University, Aberdeen, UK.

#### **Day 1: Sprint and change of direction assessment**

Timing gates were placed at the start, 5 m, 10 m and 30 m lines to record three different sprint times representing distinct qualities (first-step quickness, acceleration and speed, respectively) (Cronin and Hansen 2005). A thorough warm-up which included jogging,

dynamic stretches and a series of sub-maximum sprints was completed. At the start, participants adopted a 2-point crouched position, 30 cm back from the starting line. Two maximum sprints were performed with the best time for each split selected for further analysis. ICCs obtained from 5 m, 10 m, and 30 m sprint times were 0.78, 0.89 and 0.95 respectively.

Ability to change direction was assessed using the 505 agility test (Sheppard and Young 2006). A 15 m track was outlined with a start and stop-timing gate placed at the 10 m line. Participants sprinted from the start to the end of the 15 m track, where they then turned 180 degrees and sprinted back past the timing gate. Two trials were performed with change of direction made with the left foot, and two trials with the right foot. The best time from the four trials was selected for further analysis. The ICC obtained from the two fastest times was 0.80.

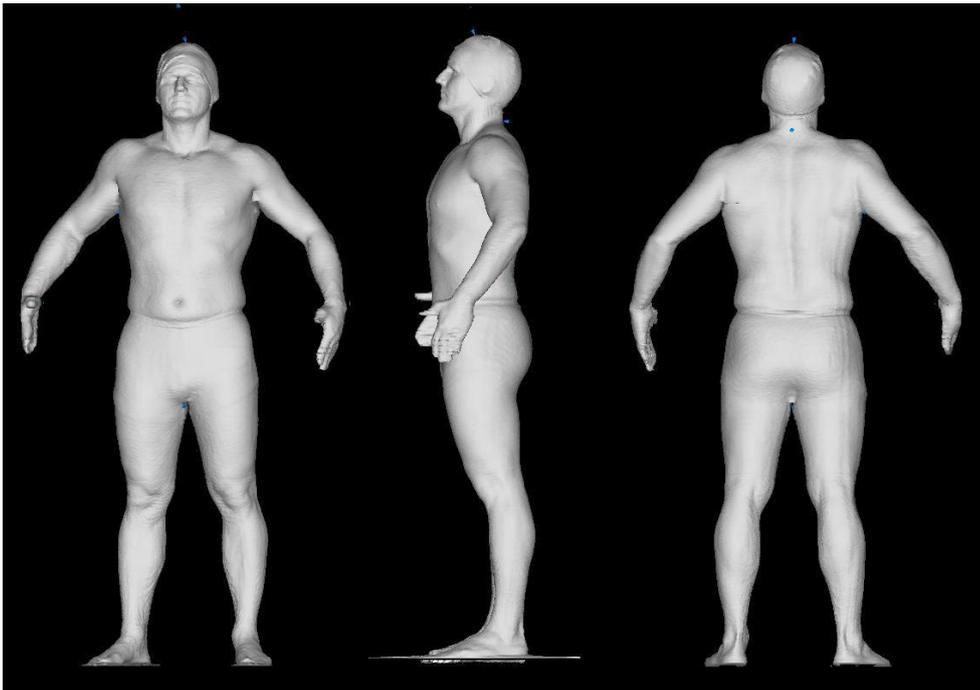
## **Day 2: Maximum strength and anthropometry assessment**

On day two of testing the participants first reported to the gymnasium where they performed 1RM tests in the back squat and deadlift in a randomised order. The athletes were accustomed to performing multiple 1RM tests in a single session as part of their regular physical assessments. To minimise the likelihood of fatigue influencing results, a 30 minute rest period was allocated between tests. Based on a predicted 1RM load, participants performed a series of warm-up sets and up to 5 maximum attempts. A minimum of 2 minutes and a maximum of 4 minutes recovery time were allocated between each attempt. Within this time frame participants self-selected when to perform the lift based on their own perception of when they had recovered. For both the squat and deadlift, a lift was deemed successful if the barbell was not lowered at any point during the ascent phase and upon completion of the movement the body posture was held erect with the knee and hip fully extended.

Anthropometric measurements were made using a Hamamatsu Bodyline scanner which used a Class I laser (eye-safe) device. A total of 14 anthropometric measurements were made, including body mass, lengths (stature, trunk, floor to hip, thigh, lower-leg), widths (shoulder, chest), and girths (chest, trunk, upper arm, hip, thigh, calf). Two scans of approximately 10 seconds in duration were made for each participant. The laser range-

finder created a pixel point cloud representation of the body surface. From these data, proprietary software rendered a polygon shell that could then be graphically shaded for viewing and inspection. Using the high resolution scanner mode, which samples using a vertical pitch of 2.5 mm, the image created (Figure 4.1) is an accurate model which can be viewed as a solid object wire-frame mesh. ICCs obtained from the anthropometric variables ranged from 0.95 to 0.99.

**Figure 4.1:** Rendered polygon shell used to measure linear anthropometric measurements



### **Day 3: Vertical jump and Explosive resistance exercise assessment**

Upon reporting to the human performance laboratory, the participants performed a thorough warm-up which included jogging on a treadmill, dynamic stretches and performance of a series of sub-maximum jumps. Once suitably prepared, two maximum vertical jumps with arms held stationary at the side of the body were performed. The jump that resulted in the greatest vertical displacement was selected for further analysis. The participants then performed maximum velocity deadlifts and jump squats using loads of 10, 20, 30, 40, 50, 60 and 70% of their previously determined 1RM's. Two repetitions were performed for each condition in a single set, with a minimum 2 minute rest period allocated between conditions and a longer rest period (up to 4 minutes) made available if the athlete felt it necessary to produce maximum performance. All Jumps and loaded resistance exercises were performed with a separate piezoelectric force platform (Kistler, Type 9281B Kistler

Instruments, Winterthur, Switzerland) under each foot capturing vertical ground reaction force (VGRF) data at 1200 Hz. Force plate data were filtered using a fourth-order, zero-phase lag Butterworth filter with a 50 Hz cutoff. Displacement, velocity and power data were calculated at the athlete's COM during unloaded jumps and at the system COM (athlete + external load) during loaded conditions. The kinematic and kinetic variables were calculated using the VGRF-time data and a forward dynamics approach that has been reported previously in the literature (Kawamori et al. 2005, Harman et al. 1990). Briefly, trials were initiated with the participant standing erect and motionless. Once data acquisition was initiated, participants performed the eccentric component of the movement to the required depth and then accelerated upwards as fast as possible. Changes in vertical velocity of the COM were calculated by multiplying the net VGRF by the intersample time period divided by the system mass. Instantaneous velocity at the end of each sampling interval was determined by summing the previous changes in vertical velocity to the pre-interval absolute velocity, which was equal to zero at the start of the movement. The position change over each interval was calculated by taking the product of absolute velocity and the intersample time period. Vertical position of the COM was then obtained by summing the position changes. Instantaneous power was calculated by taking the product of the VGRF and the concurrent vertical velocity. RFD was calculated from the slope of the VGRF-time curve extending from the transition between eccentric and concentric phases to the maximum value of the first peak. Jump height for unloaded vertical jumps was calculated using constant acceleration equations and the vertical velocity of the system at take-off (Linthorne 2001). For the deadlift and jump squat, the largest force, velocity, power and RFD values measured across the sub-maximum loads were selected for further analysis. ICC values obtained for these variables and the vertical displacement of unloaded jumps ranged from 0.94 to 0.98.

### **Statistical Analyses**

Based on findings from previous research demonstrating that force and power are related to body mass (Crewther, McGuigan and Gill 2011) and that RFD is related to the peak force value obtained (Aagaard et al. 2002), normalised values for these variables were included in addition to absolute values measured. Simple ratio scaling was used to normalise RFD values relative to the peak force of the slope from which RFD was calculated. Both ratio scaling and allometric scaling using an exponent of 0.67 were used to normalise force and power values relative to body mass (Jaric, Mirkov and Markovic 2005), with a view to establishing which scaling method provided better insight into the relationship with

performance. A value of 0.67 was selected due to its theoretical relevance and validation in multiple studies (Jaric 2002, Jaric, Mirkov and Markovic 2005, Crewther et al. 2009). Pearson correlation coefficients were used initially to quantify relationships of anthropometric, biomechanical and performance measures. Suitable predictor variables were then regressed using a best subsets approach to create two separate models. The first model included anthropometric and biomechanical predictor variables collected during the jump squat. The second model included the same anthropometric variables combined with predictor variables collected during the deadlift. The fit of each model was assessed using adjusted  $R^2$  and Mallows'  $C_p$  statistic. The regression procedures were performed using Minitab 15 statistical software (Minitab Inc. State College, PA).

## 4.4 Results

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### Intercorrelations

Average values for performance measures, maximum strength scores and basic anthropometry are displayed in Table 4.1. Intercorrelations for the biomechanical and anthropometric variables are displayed in Tables 4.2 to 4.4. The results show that a wide range of trivial to strong, positive correlations were obtained between the biomechanical variables. The results also reveal that the intercorrelations were consistently higher for variables collected during the jump squat in comparison to the deadlift. As was to be expected, some of the strongest correlations were obtained between average and peak values of the same variable. In addition, significant relationships were recorded between velocity and power during both exercises. Interestingly, peak power was the only variable which consistently exhibited significant correlations with 1RM strength measures.

**Table 4.1:** Anthropometric, strength and performance results (mean  $\pm$  SD)

| Variable           |                  |
|--------------------|------------------|
| Stature (cm)       | 181.2 $\pm$ 6.6  |
| Body Mass (kg)     | 94.2 $\pm$ 11.1  |
| Chest girth (cm)   | 118.6 $\pm$ 10.8 |
| Waist girth (cm)   | 89.9 $\pm$ 12.8  |
| Deadlift 1RM (kg)  | 191 $\pm$ 19.9   |
| Squat 1RM (kg)     | 163 $\pm$ 21.3   |
| Vertical Jump (cm) | 41.1 $\pm$ 5.1   |
| 5m sprint (s)      | 1.09 $\pm$ 0.05  |
| 10m sprint (s)     | 1.77 $\pm$ 0.08  |
| 30m sprint (s)     | 4.09 $\pm$ 0.18  |
| 505 agility (s)    | 2.58 $\pm$ 0.12  |

**Table 4.2:** Intercorrelations of biomechanical variables collected during the deadlift

|                           | 1RM Squat | 1RM Deadlift | AV    | PV    | RFDN  | APN <sup>0.67</sup> | PPN <sup>0.67</sup> | AFN <sup>0.67</sup> | PFN <sup>0.67</sup> |
|---------------------------|-----------|--------------|-------|-------|-------|---------------------|---------------------|---------------------|---------------------|
| <b>1RM Squat</b>          | 1         | 0.52*        | 0.09  | 0.17  | 0.23  | 0.23                | 0.43*               | -0.08               | -0.15               |
| <b>1RM Deadlift</b>       | 0.52*     | 1            | 0.05  | 0.01  | 0.17  | 0.21                | 0.55*               | -0.17               | -0.11               |
| <b>AV</b>                 | 0.09      | 0.05         | 1     | 0.31  | 0.16  | 0.42*               | 0.19                | -0.24               | -0.13               |
| <b>PV</b>                 | 0.17      | 0.01         | 0.31  | 1     | 0.14  | 0.37*               | 0.77*               | 0.28                | 0.17                |
| <b>RFDN</b>               | 0.23      | 0.17         | 0.16  | 0.14  | 1     | 0.03                | 0.40*               | 0.16                | 0.23                |
| <b>APN<sup>0.67</sup></b> | 0.23      | 0.21         | 0.42* | 0.38* | 0.03  | 1                   | 0.21                | 0.37                | 0.24                |
| <b>PPN<sup>0.67</sup></b> | 0.43*     | 0.45*        | 0.19  | 0.77* | 0.40* | 0.21                | 1                   | 0.17                | 0.12                |
| <b>AFN<sup>0.67</sup></b> | -0.08     | -0.17        | -0.24 | 0.28  | 0.16  | 0.37                | 0.17                | 1                   | 0.70*               |
| <b>PFN<sup>0.67</sup></b> | -0.15     | -0.11        | -0.13 | 0.17  | 0.23  | 0.24                | 0.12                | 0.70*               | 1                   |

AV = average velocity, PV = peak velocity, RFDN = RFD/peak force, APN<sup>0.67</sup> = average power/body mass<sup>0.67</sup>, PPN<sup>0.67</sup> = peak power/body mass<sup>0.67</sup>, AFN<sup>0.67</sup> = average force/body mass<sup>0.67</sup>, PFN<sup>0.67</sup> = peak force/body mass<sup>0.67</sup>, \*correlation is significant (p<0.05)

**Table 4.3:** Intercorrelations of biomechanical variables collected during the jump squat

|                           | 1RM Squat | 1RM Deadlift | AV    | PV    | RFDN  | APN <sup>0.67</sup> | PPN <sup>0.67</sup> | AFN <sup>0.67</sup> | PFN <sup>0.67</sup> |
|---------------------------|-----------|--------------|-------|-------|-------|---------------------|---------------------|---------------------|---------------------|
| <b>1RM Squat</b>          | 1         | 0.52*        | 0.29  | 0.23  | 0.29  | 0.35                | 0.34                | 0.15                | 0.33                |
| <b>1RM Deadlift</b>       | 0.52*     | 1            | 0.26  | 0.27  | 0.17  | 0.33                | 0.39*               | 0.11                | 0.32                |
| <b>AV</b>                 | 0.29      | 0.26         | 1     | 0.72* | 0.10  | 0.77*               | 0.60*               | 0.21                | 0.21                |
| <b>PV</b>                 | 0.23      | 0.27         | 0.72* | 1     | 0.41* | 0.53*               | 0.83*               | 0.29                | 0.42*               |
| <b>RFDN</b>               | 0.29      | 0.17         | 0.10  | 0.41* | 1     | -0.03               | 0.43*               | -0.09               | 0.29                |
| <b>APN<sup>0.67</sup></b> | 0.35      | 0.33         | 0.77* | 0.53* | -0.03 | 1                   | 0.74*               | 0.58*               | 0.50*               |
| <b>PPN<sup>0.67</sup></b> | 0.34      | 0.39*        | 0.60* | 0.83* | 0.43* | 0.74*               | 1                   | 0.62*               | 0.75*               |
| <b>AFN<sup>0.67</sup></b> | 0.15      | 0.11         | 0.21  | 0.29  | -0.09 | 0.58*               | 0.62*               | 1                   | 0.88*               |
| <b>PFN<sup>0.67</sup></b> | 0.33      | 0.32         | 0.21  | 0.42* | 0.29  | 0.50*               | 0.75**              | 0.88*               | 1                   |

AV = average velocity, PV = peak velocity, RFDN = RFD/peak force, APN<sup>0.67</sup> = average power/body mass<sup>0.67</sup>, PPN<sup>0.67</sup> = peak power/body mass<sup>0.67</sup>, AFN<sup>0.67</sup> = average force/body mass<sup>0.67</sup>, PFN<sup>0.67</sup> = peak force/body mass<sup>0.67</sup>, \*correlation is significant (p<0.05)

Intercorrelations for anthropometric variables revealed strong positive relationships within the measurement types but not across (Table 4.4). Body mass was shown to correlate strongly with all girths except that of the upper arm. In addition, moderate positive relationships were found when pairing body mass with shoulder width and stature.

**Table 4.4:** Intercorrelations of anthropometric variables

|                | Mass  | Chest Girth | Waist Girth | Thigh Girth | Arm Girth | Hip Girth | Calf Girth | Chest Width | Shoulder Width | Stature | Trunk Length | Hip Length | Thigh Length | Leg Length |
|----------------|-------|-------------|-------------|-------------|-----------|-----------|------------|-------------|----------------|---------|--------------|------------|--------------|------------|
| <b>Mass</b>    | 1     | 0.77*       | 0.70*       | 0.93*       | 0.16      | 0.84*     | 0.66*      | 0.06        | 0.60*          | 0.55*   | 0.31         | 0.24       | 0.03         | 0.33       |
| <b>Girths</b>  |       |             |             |             |           |           |            |             |                |         |              |            |              |            |
| Chest          | 0.77* | 1           | 0.57*       | 0.63*       | 0.09      | 0.66*     | 0.36       | 0.61*       | 0.52*          | 0.14    | 0.41*        | 0.05       | -0.17        | 0.14       |
| Waist          | 0.70* | 0.57*       | 1           | 0.72*       | 0.42*     | 0.56*     | 0.49*      | 0.07        | 0.33           | 0.11    | 0.37         | 0.06       | -0.12        | 0.12       |
| Thigh          | 0.93* | 0.63*       | 0.72*       | 1           | 0.17      | 0.78*     | 0.61*      | 0.15        | 0.47*          | 0.29    | 0.46*        | 0.23       | 0.07         | 0.29       |
| Arm            | 0.16  | 0.09        | 0.42*       | 0.17        | 1         | 0.38*     | 0.12       | 0.21        | -0.13          | -0.3    | 0.08         | -0.18      | 0.48*        | -0.29      |
| Hip            | 0.84* | 0.66*       | 0.56*       | 0.78*       | 0.38*     | 1         | 0.65*      | 0.04        | 0.39*          | -0.11   | 0.26         | -0.17      | -0.36        | -0.11      |
| Calf           | 0.66* | 0.36        | 0.49*       | 0.61*       | 0.12      | 0.65*     | 1          | 0.12        | 0.41*          | -0.06   | 0.37         | -0.10      | -0.28        | -0.05      |
| <b>Widths</b>  |       |             |             |             |           |           |            |             |                |         |              |            |              |            |
| Chest          | 0.06  | 0.61*       | 0.07        | 0.15        | 0.21      | 0.04      | 0.12       | 1           | 0.48*          | -0.06   | -0.31        | 0.09       | 0.20         | -0.05      |
| Shoulder       | 0.57* | 0.52*       | 0.33        | 0.47*       | -0.13     | 0.39*     | 0.41*      | 0.48*       | 1              | 0.28    | 0.39*        | 0.13       | -0.11        | 0.28       |
| <b>Lengths</b> |       |             |             |             |           |           |            |             |                |         |              |            |              |            |
| Stature        | 0.55* | 0.14        | 0.11        | 0.29        | -0.3      | -0.11     | -0.06      | -0.06       | 0.28           | 1       | 0.66*        | 0.93*      | 0.75*        | 0.99*      |
| Trunk          | 0.31  | 0.41*       | 0.37        | 0.46*       | 0.08      | 0.26      | 0.37       | -0.31       | 0.39*          | 0.66*   | 1            | 0.42*      | 0.08         | 0.66*      |
| Hip            | 0.26  | 0.05        | 0.06        | 0.23        | -0.18     | -0.17     | -0.10      | 0.09        | 0.13           | 0.93*   | 0.42*        | 1          | 0.90*        | 0.93*      |
| Thigh          | 0.03  | -0.17       | -0.12       | 0.07        | 0.48*     | -0.36     | -0.28      | 0.20        | -0.11          | 0.75*   | 0.08         | 0.90*      | 1            | 0.75*      |
| Leg            | 0.33  | 0.14        | 0.12        | 0.29        | -0.29     | -0.11     | -0.05      | -0.05       | 0.28           | 0.99*   | 0.66*        | 0.93*      | 0.75*        | 1          |

\* Correlation is significant (p<0.05)

Correlations between anthropometric and biomechanical variables revealed that the two sets of measurements were largely independent. The anthropometric girth variables exhibited moderate inverse relationships with the peak velocity variable; however, these correlations became non-significant when controlling for the variation explained by body mass.

To investigate the effect of body mass and relative scaling on the values obtained for biomechanical variables a series of correlation analyses were completed. The first analysis quantified the relationships between absolute values and body mass (Table 4.5). The results showed that body mass exhibited significant positive relationships with all variables except average and peak velocity. When maximum strength, power and force variables were normalised by dividing by body mass (Table 4.6) the correlations remained significant, but now revealed inverse relationships. The association between body mass and RFD became non-significant after dividing by the corresponding peak force values. Allometric scaling provided the best method of establishing body-mass independent values for maximum strength, power and force variables (Table 4.7). This was demonstrated by the attainment of non-significant correlations after dividing by body mass raised to an exponent of 0.67.

**Table 4.5:** Correlations of body mass and absolute values of biomechanical variables

|             | AV    | PV    | RFD   | AP    | PP    | AF    | PF    | 1RM Deadlift | 1RM Squat |
|-------------|-------|-------|-------|-------|-------|-------|-------|--------------|-----------|
| <b>Mass</b> | -0.20 | -0.38 | *0.51 | 0.55* | 0.42* | 0.71* | 0.81* | 0.45*        | 0.47*     |

AV = average velocity, PV = peak velocity, AP = average power, PP = peak power, AF = average force, PF = peak force, \* correlation is significant ( $p < 0.05$ )

**Table 4.6:** Correlations of body mass and isometric scaling of biomechanical variables

|             | AV    | PV    | RFDN  | APN    | PPN    | AFN    | PFN   | 1RM DeadliftN | 1RM SquatN |
|-------------|-------|-------|-------|--------|--------|--------|-------|---------------|------------|
| <b>Mass</b> | -0.20 | -0.38 | -0.04 | -0.42* | -0.71* | -0.68* | -0.71 | -0.65*        | -0.48*     |

AV = average velocity, PV = peak velocity, RFDN = RFD/peak force, APN = average power/body mass, PPN = peak power/body mass, AFN = average force/body mass, PFN = peak force/body mass, 1RM DeadliftN = 1RM deadlift/body mass, 1RM SquatN = 1RM squat/body mass, \*correlation is significant ( $p < 0.05$ )

**Table 4.7:** Correlations of body mass and allometric scaling of biomechanical variables

|      | AV    | PV    | RFDN  | APN <sup>0.67</sup> | PPN <sup>0.67</sup> | AFN <sup>0.67</sup> | PFN <sup>0.67</sup> | 1RM <sup>0.67</sup> DeadliftN | 1RM <sup>0.67</sup> SquatN |
|------|-------|-------|-------|---------------------|---------------------|---------------------|---------------------|-------------------------------|----------------------------|
| Mass | -0.20 | -0.38 | -0.04 | -0.11               | -0.14               | -0.28               | -0.26               | -0.15                         | -0.21                      |

AV = average velocity, PV = peak velocity, RFDN = RFD/peak force, APN<sup>0.67</sup> = average power/body mass<sup>0.67</sup>, PPN<sup>0.67</sup> = peak power/body mass<sup>0.67</sup>, AFN<sup>0.67</sup> = average force/ body mass<sup>0.67</sup>, PFN<sup>0.67</sup> = peak force/body mass<sup>0.67</sup>, 1RM<sup>0.67</sup> DeadliftN= 1RM deadlift/body mass<sup>0.67</sup>, 1RM<sup>0.67</sup> SquatN = 1RM squat/body mass<sup>0.67</sup>

### Relationships with performance variables

A range of correlation values were obtained between anthropometric and performance variables. All girth measurements exhibited significant ( $p < 0.05$ ) negative correlations with performance; that is, with increasing muscular girths, vertical jump, sprinting and change of direction performance decreased. However, all correlations became non-significant when controlling for the variation explained by body mass. No significant relationships were obtained between length or width measurements and performance values. The strongest correlations with performance were obtained for maximum strength scores scaled allometrically with body mass (Tables 4.8 and 4.9). For the biomechanical variables measured with sub-maximum loads, the strength of relationships was influenced by scaling. In general, absolute values for force, power and PRDF exhibited small non-significant correlations with performance. However, once these variables were normalised relative to body mass and peak force respectively, the strength of the correlations increased with most variables demonstrating statistical significance ( $p < 0.05$ , Tables 4.8 and 4.9).

**Table 4.8:** Relationships between performance and biomechanical variables collected during the deadlift

|                                   | Vertical Jump | 5 m    | 10 m   | 30 m   | 505    |
|-----------------------------------|---------------|--------|--------|--------|--------|
| <b>1RM Dead/BM<sup>0.67</sup></b> | 0.65*         | -0.60* | -0.81* | -0.81* | -0.75* |
| <b>AV</b>                         | 0.21          | -0.19  | -0.10  | -0.11  | -0.12  |
| <b>PV</b>                         | 0.51*         | -0.47* | -0.49* | -0.51* | -0.28  |
| <b>AP/BM<sup>0.67</sup></b>       | 0.51*         | -0.35* | -0.32  | -0.49* | -0.20  |
| <b>PP/BM<sup>0.67</sup></b>       | 0.49*         | -0.44* | -0.48* | -0.56* | -0.48* |
| <b>AF/BM<sup>0.67</sup></b>       | 0.74*         | -0.31  | -0.40* | -0.50* | -0.27  |
| <b>PF/BM<sup>0.67</sup></b>       | 0.54*         | -0.27  | -0.21  | -0.36  | -0.36  |
| <b>RFD/PF</b>                     | 0.16          | -0.39* | -0.14  | -0.19  | -0.38* |

\*Correlation is significant (p<0.05)

**Table 4.9:** Relationships between performance and biomechanical variables collected during the jump squat

|                                    | Vertical Jump | 5 m    | 10 m   | 30 m   | 505    |
|------------------------------------|---------------|--------|--------|--------|--------|
| <b>1RM Squat/BM<sup>0.67</sup></b> | 0.80*         | -0.56* | -0.73* | -0.82* | -0.70* |
| <b>AV</b>                          | 0.61*         | -0.54* | -0.56* | -0.64* | -0.51* |
| <b>PV</b>                          | 0.84*         | -0.60* | -0.70* | -0.80* | -0.63* |
| <b>AP/BM<sup>0.67</sup></b>        | 0.34          | -0.47* | -0.52* | -0.62* | -0.40* |
| <b>PP/BM<sup>0.67</sup></b>        | 0.67*         | -0.57* | -0.71* | -0.80* | -0.45* |
| <b>AF/BM<sup>0.67</sup></b>        | 0.27          | -0.24  | -0.45* | -0.47* | -0.33  |
| <b>PF/BM<sup>0.67</sup></b>        | 0.44*         | -0.37  | -0.61* | -0.60* | -0.35  |
| <b>RFD/PF</b>                      | 0.43*         | -0.41* | -0.36  | -0.40* | -0.51* |

\*Correlation is significant (p<0.05)

## **Performance prediction models**

Two separate best subsets regression models were developed for each performance measure (Table 4.10). The first set of models included normalised strength measures, the strongest anthropometric predictors and normalised biomechanical variables collected during maximum speed deadlifts. The second set of models included the same strength and anthropometric measurements as used in the first set, but included normalised biomechanical variables from the jump squat instead of the deadlift. In general, similar results were obtained for both sets of models, with three predictor variables providing the most appropriate balance between explained variance and model complexity. The greatest amount of performance variance could be explained in the 30 m sprint, followed by the vertical jump, 10 m sprint, 505 agility test and 5 m sprint (Table 4.10). For both sets of models performance was best explained by combining normalised maximum strength scores and biomechanical variables rather than anthropometric measurements. Performance in the vertical jump was best explained by an athlete's maximum strength capabilities and their ability to develop high velocities, whereas, performance in the 5 m sprint and 505 agility tests were best explained by maximum strength scores and RFD. Predictor models for 10 m and 30 m sprints featured primarily maximum strength scores and average or peak power values.

**Table 4.10:** Best single-, two- and three-predictor regression models for performance measures combining anthropometric, maximum strength and biomechanical variables collected during the deadlift or jump squat.

|                      | Deadlift                    |                    | Jump Squat                  |                    |
|----------------------|-----------------------------|--------------------|-----------------------------|--------------------|
|                      | Best Predictor              | Adj R <sup>2</sup> | Best Predictor              | Adj R <sup>2</sup> |
| <b>Vertical Jump</b> |                             |                    |                             |                    |
| Single predictor     | 1RM DeadN                   | 0.62               | PV                          | 0.67               |
| Two predictors       | 1RM DeadN, PV               | 0.72               | PV, Mass                    | 0.78               |
| Three predictors     | 1RM DeadN, PV, PFN          | 0.78               | PV, AV, 1RM DeadN           | 0.82               |
| <b>5m Sprint</b>     |                             |                    |                             |                    |
| Single predictor     | 1RM SquatN                  | 0.33               | 1RM SquatN                  | 0.33               |
| Two predictors       | 1RM SquatN, 1RM DeadN       | 0.38               | 1RM SquatN, RFDN            | 0.39               |
| Three predictors     | 1RM SquatN, 1RM DeadN, RFDN | 0.42               | 1RM SquatN, APN, RFDN       | 0.43               |
| <b>10m Sprint</b>    |                             |                    |                             |                    |
| Single predictor     | 1RM SquatN                  | 0.64               | 1RM SquatN                  | 0.64               |
| Two predictors       | 1RM SquatN, PFN             | 0.68               | 1RM SquatN, PPN             | 0.74               |
| Three predictors     | 1RM SquatN, PPN, Mass       | 0.73               | 1RM SquatN, PPN, Mass       | 0.76               |
| <b>30m Sprint</b>    |                             |                    |                             |                    |
| Single predictor     | 1RM DeadN                   | 0.67               | 1RM DeadN                   | 0.67               |
| Two predictors       | 1RM DeadN, PPN              | 0.73               | 1RM SquatN, PPN             | 0.80               |
| Three predictors     | 1RM SquatN, 1RM DeadN, APN  | 0.78               | 1RM DeadN, Mass, APN        | 0.86               |
| <b>505 Agility</b>   |                             |                    |                             |                    |
| Single predictor     | 1RM SquatN                  | 0.51               | 1RM SquatN                  | 0.51               |
| Two predictors       | 1RM SquatN, 1RM DeadN       | 0.56               | 1RM SquatN, RFDN            | 0.60               |
| Three predictors     | 1RM SquatN, 1RM DeadN, RFDN | 0.60               | 1RM SquatN, 1RM DeadN, RFDN | 0.67               |

AV = average velocity, PV = peak velocity, RFDN = RFD/peak force, APN = average power/body mass<sup>0.67</sup>, PPN = peak power/body mass<sup>0.67</sup>, AFN = average force/ body mass<sup>0.67</sup>, PFN = peak force/body mass<sup>0.67</sup>, 1RM DeadliftN = 1RM deadlift/body mass<sup>0.67</sup>, 1RM SquatN = 1RM squat/body mass<sup>0.67</sup>

## 4.5 Discussion

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The results of this study demonstrate that a large amount of variance in performance of general movement patterns common to many sports can be explained by an athlete's relative maximum strength and their ability to produce high outputs in certain biomechanical variables. Using the adjusted coefficient of determination, between 70 to 80% of the variance in vertical jump, 10 m sprint and 30 m sprint performance could be explained by relatively simple three factor models. For the 505 agility and 5 m sprint tests the explained variance decreased to between 40 and 65%, indicating that factors other than those assessed in the present study are important in determining overall performance. More accurate models may require inclusion of technique related factors to increase understanding of performance, particularly for the acceleration and change of direction tasks. However, higher within-individual variability measured in the 505 agility and 5 m sprint tests may also have contributed to reduced explanatory power of the models.

The results of the present study support the findings from a number of previous investigations demonstrating strong relationships between maximum strength and measures of athletic performance (Wisloff et al. 2004, Peterson, Alvar and Rhea 2006, Baker and Nance 1999). Data collected from the most recent studies have also shown that the strength of the relationship can be enhanced by normalising maximum strength values relative to body mass (McBride et al. 2009). However, a range of factors including the variation in the sample's athletic capabilities and body masses are likely to impact on the strength of relationships obtained. Peterson et al. (2006) investigated the relationship between 1RM back squat values and performance in jumping, sprinting and agility tests. The participants comprised a heterogeneous group of male and female college athletes from a variety of sports. When modelling the entire group, the relationships between maximum strength and performance measures were strong and largely unaffected after normalising to body mass. When relationships were re-assessed post stratification by gender, the strength of relationships between absolute values of maximum strength and performance substantially decreased and became non-significant for the male group. Upon scaling maximum strength values relative to body mass the strength of relationships increased for both males and females with significant values obtained for each gender. The results obtained by Peterson et al. (2006) suggest that when large variations in performance and strength exist within a sample, absolute values of maximum strength are sufficient to reveal relationships between variables. In contrast, when variation is decreased the

magnitude of the correlation statistic is reduced (Goodwin and Leech 2006), and normalisation of maximum strength scores may be required to identify relationships.

The majority of previous studies that have normalised maximum strength scores when investigating the relationship between strength and performance have done so using simple ratio scaling (Kawamori et al. 2005, Peterson, Alvar and Rhea 2006, Baker and Nance 1999). This approach, however, assumes that there is a linear relationship between body mass and strength. Most data contradict this assumption and demonstrate that whilst a positive relationship between strength and body mass does exist, the strength values of progressively heavier individuals fall below projected linear values (Jaric, Mirkov and Markovic 2005). More appropriate scaling may be achieved when using methods that assume non-linearity between body mass and strength. The theory of geometric similarity proposes that human bodies possess the same shape and therefore differ only in size (Jaric, Mirkov and Markovic 2005). As a consequence of this theory, it is predicted that any area measurement is proportional to body mass raised to the power 0.67 (e.g.  $\text{area} \propto \text{BM}^{0.67}$ ). As force production is proportional to muscle physiological cross-sectional area (Manso-Garcia et al. 2008), based on the theory of geometric similarity, maximum strength scores should be divided by body mass raised to the power 2/3 when attempting to control for the effects of mass. This procedure has been used extensively to scale strength with body mass in powerlifting and Olympic weightlifting (Manso-Garcia et al. 2008, Challis 1999) and is commonly referred to as allometric scaling in the literature. In the sport of Rugby union, there is considerable variation in body mass across the different playing positions. Previous research has shown that, on average, elite forwards are approximately 20% heavier than elite backs (Duthie et al. 2006). In addition, heavier forwards tend to produce greater maximum strength values, whereas, lighter backs tend to perform better in tests that require high velocities such as in jumping and sprinting (Duthie, Pyne and Hooper 2003). In the present study, maximum strength scores were shown to be strongly related to body mass. The results also demonstrated that a relationship still existed when using ratio scaling, however, the direction changed to reveal an inverse relationship. The results imply that absolute maximum strength scores favour the heaviest athletes, whereas normalising values by ratio scaling favours the lightest athletes. When maximum strength scores were scaled allometrically using an exponent of 0.67 the correlations with body mass became non-significant, demonstrating that this method of scaling is more effective than the ratio method for creating strength measures that are independent of body mass. Similar findings were obtained by Crewther et al. (2011) using a sample of rugby athletes similar to those participating in the present study. Initial correlations between body mass and absolute

values of strength scores were shown to demonstrate significant positive correlations. Ratio scaling of maximum strength scores then resulted in correlations indicating an inverse relationship between body mass and strength. Finally, allometric scaling was shown to be a superior method for producing maximum strength scores which were independent of body mass (Crewther, McGuigan and Gill 2011). For the allometric scaling procedures the authors derived their own scaling exponents for the specific group of athletes based on modelling the log transformed data using a least-squares approach. The derived exponents for body mass and strength were shown to be consistent with the theoretical value of 0.67. The results from Crewther et al. (2011) and the present study demonstrate that for sports such as rugby union where considerable variation in body mass exists, maximum strength values should be allometrically scaled when evaluating the athletes.

Due to the high velocity and explosive nature of many sporting tasks, a number of studies have attempted to quantify the relationship between variables such as power and RFD with measures of performance (Cronin and Sleivert 2005, McLellan, Lovell and Gass 2011, Sleivert and Taingahue 2004). Results have been more varied than those quantifying relationships between maximum strength and performance. Some studies have reported strong relationships (McLellan, Lovell and Gass 2011, Sleivert and Taingahue 2004)(McLellan, Lovell and Gass 2011), whereas others have reported independence between the factors (Kukulj et al. 1999). Inconsistencies may be due to a number of factors, including the exercise and loads used to obtain variables, variation in scaling methods, and the procedures used to calculate actual values (Cronin and Sleivert 2005). Some researchers have proposed that maximum strength acts as a general base influencing an athlete's ability to express other key mechanical variables such as power and RFD (Tan 1999, Cormie, McGuigan and Newton 2011). These proposals are based on cross-sectional research highlighting strong inter-relationships between the variables (Cronin, McNair and Marshall 2003), and longitudinal studies demonstrating improvements in power and RFD when performing resistance training interventions designed to enhance maximum strength (Cormie, McGuigan and Newton 2011). Due to these strong inter-relationships and proposed association between sporting activities and mechanical variables reflecting explosive force production, it has been suggested that performance in various sporting tasks may be better explained by combining mechanical variables rather than selecting single factors in isolation (Cronin and Sleivert 2005). The regression models developed in the present study support this hypothesis. However, it is also clear that performance in the tasks studied in this investigation were principally explained by normalised maximum

strength measures, and the addition of other mechanical variables such as average force, power, velocity and RFD contributed substantially less.

The models obtained in the present study also revealed that the best combinations of variables were to some extent influenced by the nature of the activity. For example, RFD featured only in models predicting performance in the 5 m sprint and 505 agility test. In both these activities performance is largely determined by the athlete's ability to accelerate their own body mass from an initial state of low velocity. Research has shown that greater propulsive forces are generated when accelerating in comparison to sprinting at faster velocities (Cronin and Hansen 2006). The combination, therefore, of both large maximum strength and RFD values would provide effective transition from low to high velocities in a short space of time. Based on similar reasoning, it may be expected that models predicting vertical jump performance which also requires athletes to transition from low to high velocities would also feature maximum strength and RFD values. Indeed, a recent investigation established that peak RFD values measured during vertical jumps correlated strongly with jump height in physically active men (McLellan, Lovell and Gass 2011). However, the vertical jump features a single discrete movement in which performance is determined by the velocity at take-off, which is approximated very closely by the peak velocity obtained during the movement (Linthorne 2001). In contrast, performances in the 5 m sprint and 505 agility test are dependent upon a more complex series of movements which progressively increase the velocity of the body. Due to the cause and effect relationship between take-off velocity and performance in the vertical jump, it is unsurprising that the regression models identified peak velocity as a primary factor, especially as the testing movements were outwardly similar to the performance action. For the 10 m and 30 m sprints the regression models highlighted the combination of strength and power values as the best predictors of performance. As the distance of the sprint increases, velocity and therefore contact time with the ground decreases (Cronin and Hansen 2006). Mechanical power may reflect an athlete's ability to generate substantial ground reaction forces over short time periods and their capacity to store and release mechanical energy (Weyand et al. 2000), all of which would be important in influencing performance in these sprints. Further work is required to assess the extent to which specificity may occur between performance and the ability to express different mechanical variables.

The use of two distinct resistance exercises (deadlift and jump squat) to collect biomechanical data revealed that the explanatory power of regression models is influenced

by the selected movement. In general, the two sets of regression models selected similar variables as best predictors for each of the performance tests (Table 4.10), demonstrating that whilst combining specific mechanical variables with maximum strength may have a relatively small effect on the explanatory power of the model, selection of the most appropriate variables is consistent. The models incorporating biomechanical variables collected during the jump squat consistently explained more of the variation in performance than those including data collected during the deadlift. This finding is in agreement with results published from a recent study investigating the predictive ability of power values collected during a traditional squat or jump squat on sprinting performance. Recruiting a sample of well-trained sprinters, Requena et al. (2011) reported that stronger correlation coefficients were obtained for absolute and relative power values collected during the jump squat in comparison with the same variables collected during the traditional squat. The authors proposed that the ability to accelerate the resistance throughout the entire concentric phase of the jump squat more closely match the kinematics of sprinting and therefore explain the stronger correlation values obtained (Requena et al. 2011). The concept of kinematic similarity was most evident in the regression models applied to the vertical jump in the present study, where substantially more of the variance was explained by models featuring velocity values collected during the closely related jump squat.

The biomechanical variables measured in the present study represent those most frequently employed in research investigating resistance training practices. Additional variables relating force and time have been described by influential researchers in the field of strength and conditioning (Tidow 1990, Zatsiorsky 1995); however, due to inconsistent terminology and limited theoretical underpinnings these less traditional variables have been studied less frequently. Zatsiorsky (1995) introduced a group of variables which he termed starting strength (force at 30 ms), impulse at 100 ms, and the S- and A-gradients which characterise the derivative of the force-time curve at different stages of a discrete action. Cronin et al. (2003) subsequently investigated the interrelationships between the traditional variables of force and power and the novel variables defined by Zatsiorsky (1995). Using a supine resistance machine to perform jump squats, the authors reported that the correlations within the sets of variables were greater than those between. As a result, the authors concluded that the novel variables may partly reflect strength qualities not measured by the traditional variables of force and power. However, the data collection procedures used by Cronin et al. (2003) did not include velocity or RFD which are partly independent to force and power, and potentially could have related more strongly to the novel variables. In pilot testing for the present study the variables introduced by Zatsiorsky

(1995) were included in the data collection protocol. However, the novel variables demonstrated reduced reliability in comparison to those ultimately used in the study. In addition, it was reasoned that the combination of force, velocity, power and RFD variables provided sufficient information regarding distinct features of the force-velocity and force-time curves. Nevertheless, it is acknowledged that there may be many biomechanical variables beyond those investigated in the present study which can better explain performance of common sporting tasks.

## 4.6 Summary and Conclusion

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The results of the present study demonstrate that relative maximum strength of athletes is the basic quality that determines their ability to perform various fundamental sporting tasks. This finding is closely aligned with the primary goal of training practices employed by powerlifters that seek to increase maximum strength whilst minimising the hypertrophic response which would place them at a competitive disadvantage. As was discussed in chapter three of this thesis, maximum strength as measured through performance of a complex movement is dependent upon a variety of factors. At present, it is not fully understood if the relationship between maximum strength and performance would be altered if athletes employed selected training practices developed by powerlifters that are designed to improve performance in a testing movement rather than enhance maximum strength capabilities per se. The results of the present study also demonstrate that relative maximum strength in isolation only explains approximately 35 to 65% of the variation in performance of jump, sprint and change of direction tests. Greater understanding and predictive ability can be obtained by combining normalised maximum strength values with biomechanical variables measured during performance of explosive resistance exercises. For certain tests such as the vertical jump and 30 m sprint, as much as 90% of the variation (as measured by the unadjusted coefficient of determination) in performance can be explained by combining the most suitable strength and biomechanical variables. Therefore, contemporary training practices developed by powerlifters to improve variables such as power, velocity and RFD may be beneficial for general athletes if the practices themselves prove effective.

## CHAPTER 5. BIOMECHANICAL MODEL

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### 5.1 Prelude

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In order to assess the biomechanical stimulus of the contemporary training practices identified in chapters two and three, a range of internal and external mechanical variables required calculation. All external variables could be calculated from GRF data and positional information obtained from the external resistance. However, calculation of internal variables required the use of biomechanical models that could be scaled for each participant. For complex movements incorporating multiple joint actions, models that represent the body as a collection of interconnected rigid segments are frequently used. The equations of motion for individual segments can be calculated with relative ease based on knowledge of segment kinematics, inertial properties of the body, and the magnitude of external forces applied to the system. The segment kinematic data itself can provide useful information regarding body postures and movement strategies employed. However, the goal of most biomechanical analyses is to quantify forces and torques to better understand the muscular effort produced and the potential that exists for injury. The purpose of this chapter is to provide a brief treatise of the kinematic and kinetic models used to calculate the internal variables for this project.

## 5.2 Kinematics

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Kinematics is a subdivision of mechanics that deals with the geometry of motion without considering the forces that cause the motion (Zatsiorsky 1998). In sports and clinical settings, kinematic variables are collected to assess the movement strategies selected by individuals to perform specific movements. The measurement of kinematic variables and therefore descriptions of human movement can be made using a range of methods and instrumentation. Near-instantaneous measurements can be obtained when recording instruments are attached directly to the body (Robertson et al. 2004). Examples include electrogoniometers (Rowe et al. 2000, Hawkins 2000), accelerometers (Mayagoitia, Nene and Veltink 2002, James 2006) and magnetic sensors (McKean, Dunn and Burkett 2010, Mills et al. 2007). In the field of sports biomechanics, kinematic variables are typically collected using image based motion capture systems (Robertson et al. 2004). For the current project, a 3D digital optical motion capture system was used. The system measures human movement by utilising motion capture cameras that track the position of small markers affixed to the body's surface through the reflection of light. Once the positional data are known, the orientation of each body segment can be estimated using various kinematic models. Data collected from multiple segments can then be used to calculate joint angles, joint velocities and accelerations. The following sections detail the methods and models used to collect kinematic data for the project.

### Locating markers in space

For sport biomechanics applications it is currently recommended that 3D optical motion capture systems include a minimum of six cameras to collect adequate data (Milner 2008). For the current project the number of cameras used to collect data ranged from seven to nine. Each camera creates a two-dimensional image that contrasts the background with the light reflected from the spherical markers affixed to the participant's body. Based on a pre-system calibration the position and orientation of each camera is defined relative to an origin point selected in the laboratory. Using this information each camera reconstructs the marker position data to represent a single line projected back into the capture volume (Vicon 2002). The intersections of projected lines from multiple cameras are then used to define the three-dimensional coordinates of each marker (Vicon 2002). For the current project the cameras were arranged to create a capture volume of approximately 1600 mm (anterior-posterior) by 2800 mm (medial-lateral) by 2200 mm (vertical). This capture volume

was selected to maximise the resolution of the individual markers. The placement and orientation of the cameras were extensively piloted to minimise the likelihood of markers being occluded during data capture.

## **Reference Systems and Marker Sets**

To quantify the three-dimensional motion of the human body using optical motion capture it is essential to establish reference systems affixed to the environment and the individual body segments. A fixed Global Cartesian Reference System (GCRS) representing the space of the external environment was created for the capture volume during calibration of each testing session. Local Cartesian Reference Systems (LCRS) were affixed to individual body segments through the placement of a minimum of three non-collinear markers. As the LCRS and corresponding body segment are considered rigid in each of the models used in this project, the motion of the LCRS and corresponding segment are considered equivalent (Yamaguchi 2001). Orientation of a body segment relative to the external environment was determined by measuring the relative orientation of the LCRS and GCRS. Importantly, once the relative location and orientation of the two reference frames were known, points of interest in one frame could be expressed in the other (Zatsiorsky 1998). This enabled positional information of important landmarks such as the centre of mass of a segment to be transformed from the LCRS to GCRS so that variables such as segment displacement and velocity could be calculated. There are numerous well defined marker configurations that have been used by researchers to affix LCRSs' to the different body segments (Robertson et al. 2004). These configurations are commonly referred to as marker sets and should adhere to the recommendations outlined by Söderkvist and Wedin (Söderkvist and Wedin 1993):

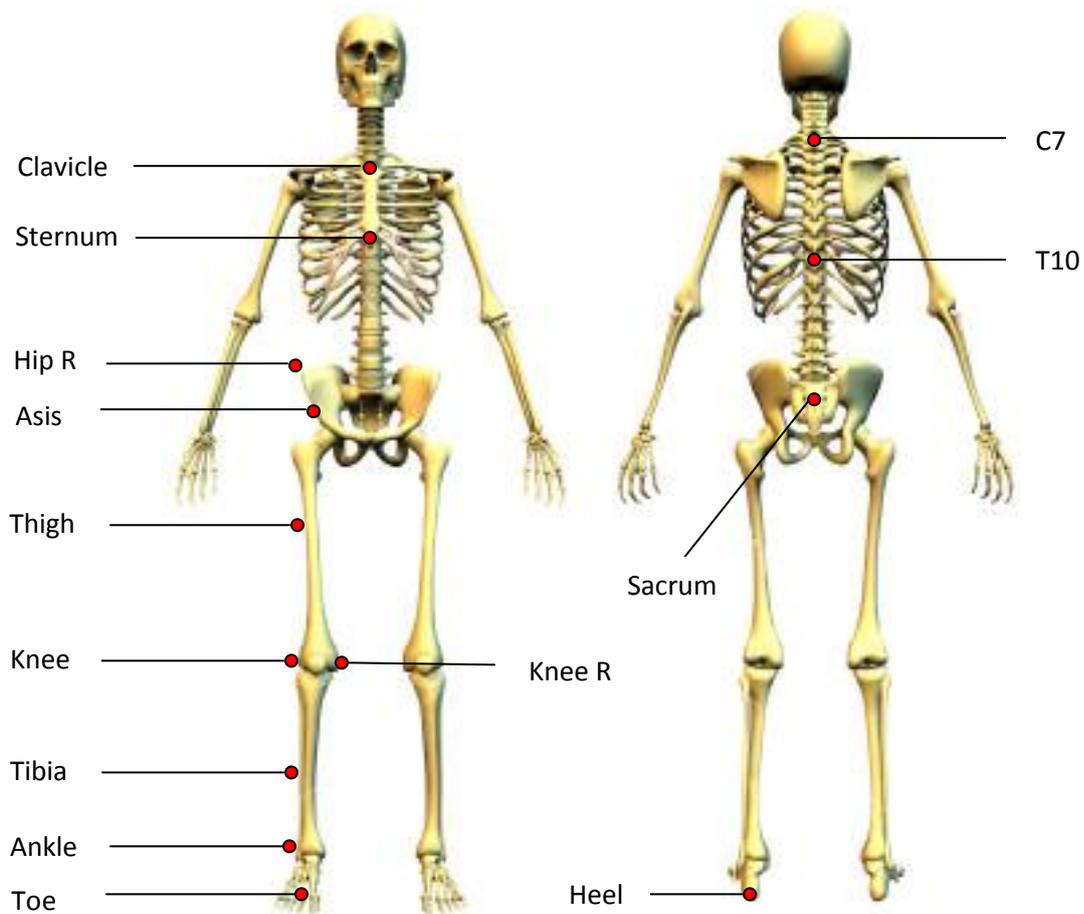
1. At least three points are required for each segment.
2. The points should be as widely spaced as possible.
3. The points should not be collinear.
4. Markers should be clearly linked to an anatomical reference frame, usually based on bony anatomy.
5. Markers should move as little as possible with respect to the underlying bone, therefore areas of thick adipose tissue or large skin movements should be avoided.
6. Markers should not oscillate as the participant moves.
7. Markers must be clearly visible to at least two cameras throughout the movement or

they will be impossible to track.

8. Markers should not be placed where they impede or block movement or where they are in danger of being knocked off.
9. Excessive numbers of markers should be avoided.

For the current project an enhanced version of the standard gait analysis marker set was used. In addition to the standard 13 markers placed on the pelvis and lower extremities (Kadaba, Ramakrishnan and Wooten 1990), the enhanced marker set included 4 markers placed on the torso and 4 redundant markers placed on the pelvis and knee to assist in reconstruction if markers became occluded. The marker set used is illustrated in Figure 5.1. Similar marker sets have been used in previous studies investigating the biomechanics of resistance training movements (Hwang, Youngeun and Youngho 2009). Employing the standard gait analysis set as a basis for marker placement provides several advantages and disadvantages for sports biomechanists (Milner 2008). The advantages include the extensive field testing over the past 20 years. In addition, widespread use of the marker set has prompted manufacturers of motion capture systems to develop software which automates the majority of the data processing required. Vicon's Nexus software (Oxford Metrics, UK) was used for the current project to process the kinematic and kinetic models stemming from the marker set employed. The primary disadvantages of the standard marker set is that it may oversimplify certain segments (e.g. the foot), and may be inappropriate for use during movements that create large impacts (Milner 2008).

**Figure 5.1:** Marker set used for project



For clarity the figure illustrates a unilateral set; however, markers were placed bilaterally.

| Marker Name    | Marker Location  |
|----------------|--|
| C7             | Spinous process of the 7 <sup>th</sup> cervical vertebrae  |
| Clavicle       | Jugular notch where the clavicle attaches to the sternum   |
| Sternum        | Xiphoid process of the sternum   |
| T10            | Spinous process of the 10 <sup>th</sup> thoracic vertebrae   |
| Hip Redundant  | Iliac crest at the mid-axillary line   |
| Asis           | Anterior superior iliac spine  |
| Sacrum         | Mid-way between the posterior superior iliac spines  |
| Thigh          | Lower lateral 1/3 surface of the thigh aligned in the plane that contains the hip and knee joint centres |
| Knee           | Lateral epicondyle of the femur  |
| Knee Redundant | Medial epicondyle of the femur   |

|       |  |
|-------|--|
| Tibia | Lower later 1/3 surface of the leg aligned in the plane that contains the knee and ankle joint centres |
| Ankle | Lateral malleolus  |
| Toe   | Second metatarsal head   |
| Heel  | Calcaneous at the same height as the toe marker  |

### **Kinematic Models**

Based on the marker set adopted, an upper (Gutierrez-Farewik, Bartonek and Saraste 2006) and lower body model (Davis et al. 2004, Kadaba, Ramakrishnan and Wooten 1990) were used to affix LCRSs' to the thorax, pelvis, thigh, shank and foot. The same models were also used to determine subject specific locations of joint centres. The following sections outline the models used for each segment.

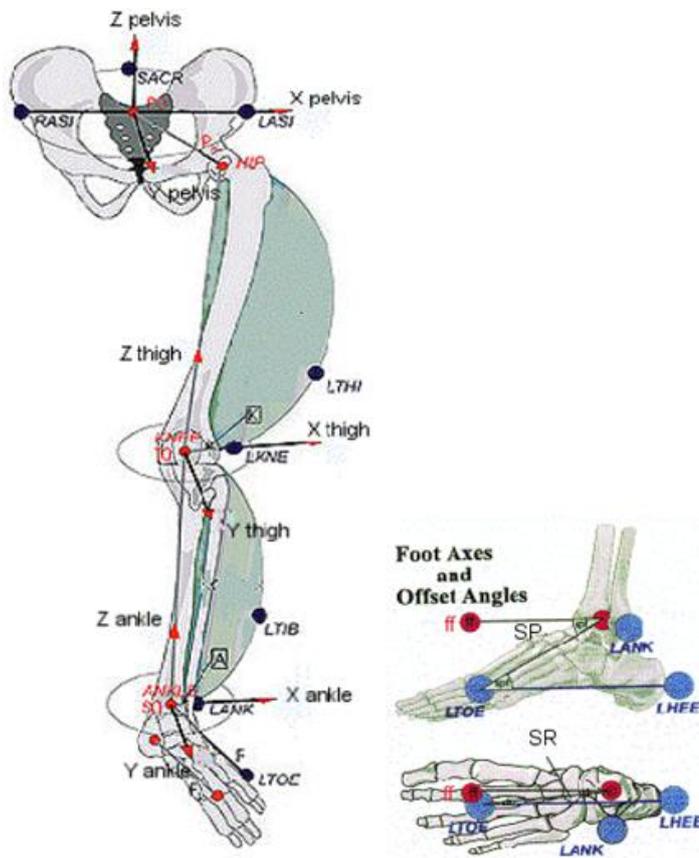
### **Upper body**

#### Thorax

The primary axis of the thorax is defined as the Z axis which is directed from the midpoint of the T10 and sternum markers to the midpoint of the C7 and clavicle markers. A secondary X axis is then created, oriented anteriorly and directed from the midpoint of the C7 and T10 markers toward the midpoint of the clavicle and sternum markers. A third perpendicular axis is created which is directed laterally towards the left-hand side of the body. The origin of the thorax is located at the clavicle with an offset equal to half the marker diameter. For kinetic modelling of the upper body segment the joint centre of the lumbar spine is taken as the position of the 5<sup>th</sup> lumbar vertebrae. The joint centre is calculated to lie along the Z axis of the pelvis 0.925 times the distance between hip joint centres.

## Lower body

The orientation and location of the LCRSs' for the pelvis, femur, tibia and foot are illustrated in Figure 5.2.



**Figure 5.2:** Representation of the standard lower body gait analysis marker set and kinematic model

### Pelvis

As shown in Figure 5.3, the axis system of the pelvis is defined by three markers positioned over the left and right anterior superior iliac spines (ASIS) and the sacrum. The pelvic origin is defined as the mid-point of the Y axis joining the ASIS markers. A plane is then defined from two vectors, the first joining the ASIS markers, and the second jointing the right ASIS to the sacrum. The Z axis is orientated upwards, perpendicular to this plane, and the X axis orientated anteriorly from the ZY plane. The location of the hip joint centres (HJC) are approximated relative to the pelvic origin. Figure 5.3 illustrates the variables and parameters

required for calculation of the left HJC coordinates. The model was developed by Davis et al. (2004) using radiographic examination data from twenty five hip studies. Mean values for the parameters  $\theta$  and  $\beta$ , and scaling functions to fit the model for each participant based on leg length ( $L_{leg}$ ) and distance between ASIS markers were developed. Specifically,  $\theta$  and  $\beta$  were found to be  $28.4 (\pm 6.6^\circ)$  and  $18.0 \pm (4.0^\circ)$  respectively. The scaling factor  $C$  (in meters) was predicted through linear regression as

$$C = 0.115L_{leg} - 0.0152 \quad (\text{eq 5.1})$$

With this, the location (in meters) of the HJC in pelvic coordinates  $(x, y, z)$  relative to the embedded LCRS is calculated as

$$x = (-x_{dis} - r_m) \cos(\beta) + C \cos(\theta) \sin(\beta) \quad (\text{eq 5.2})$$

$$y = S \left( C \sin(\theta) - \frac{d_{ASIS}}{2} \right) \quad (\text{eq 5.3})$$

$$z = (-x_{dis} - r_m) \sin(\beta) - C \cos(\theta) \cos(\beta) \quad (\text{eq 5.4})$$

where:

$S$ : +1 for right side, -1 for left side

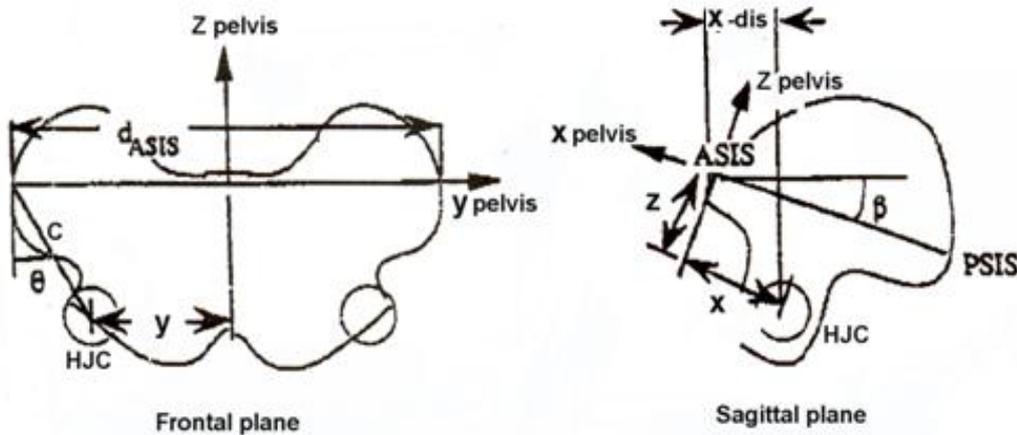
$d_{ASIS}$ : Inter-ASIS distance, measured in static trial by motion capture system, or entered manually during clinical examination for obese people

$x_{dis}$ : Anterior-posterior component of the ASIS – greater trochanter distance, measured by clinical examination or given by regression equation

$$x_{dis} = 0.1288L_{leg} - 48.56 \quad (\text{eq 5.5})$$

$r_m$ : Radius of marker in metres

**Figure 5.3:** Hip joint centre calculation, based on Davis model



### Femur

The Y-Z plane of the femur axis system is defined to lie in the plane containing the HJC, the thigh marker and knee marker placed over the lateral epicondyle. The femur origin is located at the knee joint centre which is taken to be at the level of the lateral femoral epicondyle with an offset in the Y-Z plane, equal to half the width of the knee (measured as the distance between femoral condyles). The primary Z axis is orientated from the knee joint centre to the hip joint centre. The Y axis therefore lies between the knee joint centre and knee marker. The cross-product of unit vectors along the Z and Y axes provide the orientation of the X axis which is directed towards the anterior aspect of the knee.

### Tibia

The tibia axis system is defined using a similar algorithm to that used for the femur, with the knee joint centre and, tibial and lateral malleolus markers used as reference points. The ankle joint centre which also represents the origin of the tibia axis system is located at the lateral malleolus site with an offset value equal to half the width of the ankle.

## Foot

The foot is defined by a single vector  $F$ , which is determined by the relative orientation of two segments created within the foot and ankle complex. The first segment is constructed using the long axis of the foot (heel to toe) as the primary axis. A second foot segment is constructed using the toe and ankle joint centre as the primary axis. The foot vector is then established by joining the ankle joint centre with a virtual foot point ( $ff$ ), as shown in Figure 5.2. The position of the virtual marker and resulting foot vector are calculated by rotating the second segment about two orthogonal axes. The amounts of these rotations are determined in the static calibration session, as static offset angles, and are then applied to dynamic trial data. The first offset value, static plantarflexion ( $SP$ ), is calculated as a rotation about the ankle flexion axis. This angle is measured between the line joining the ankle joint centre and the toe marker, and the line joining the heel marker and the toe marker. The second rotation, static foot rotation ( $SR$ ), is about a foot rotation axis that is perpendicular to the foot vector (after applying the static plantarflexion offset) and the ankle flexion axis.

## **Calculation of joint angles**

The orientation of the upper body segment is calculated relative to the GCRS with the anteroposterior and mediolateral planes aligned with the body. For the lower extremities, joint angles are calculated through the relative rotation of the LCRS above and below the joint (e.g. hip angles are calculated from the relative orientation of the pelvis LCRS and thigh LCRS). When the joint is in a neutral position the proximal and distal LCRSs' are aligned (Ramakrishan and Kadaba 1991). As movement occurs at the joint the relative orientation of LCRSs' change based on the degree of motion. At each time interval the relative orientation of the coordinate systems can be quantified, thereby providing information on instantaneous joint angles. In the current project, the relative orientation of coordinate systems was quantified by calculating Euler angles (comprise three angular parameters that specify the orientation of a body with respect to a reference axes). This method is based on the knowledge that any rigid body orientation can be achieved by composing three successive rotations around an orthogonal coordinate system that moves with the object (Zatsiorsky 1998). Because finite rotations in three-dimensional space are non-commutative, there are 12 sequences of rotations that can be used. The choice of rotation order is important as it affects the joint angles calculated (Blankevoort, Huiskes and Lange 1988). In the current project the first rotation was performed around the mediolateral axis (flexion/extension), then the anteroposterior axis (abduction/adduction), and finally, the vertical axis (internal/external rotation) (Figure 5.4). This sequence of rotation is commonly

used in human movement studies and reflects the successive amounts of rotation that generally occurs in three-dimensions for most joints (Robertson et al. 2004, Ramakrishan and Kadaba 1991). Rotations were calculated with the proximal LCRS held fixed and the distal segment assumed to rotate successively from the neutral aligned orientation to its current configuration. The following matrices express rotations around the mediolateral, anteroposterior, and vertical axes, respectively.

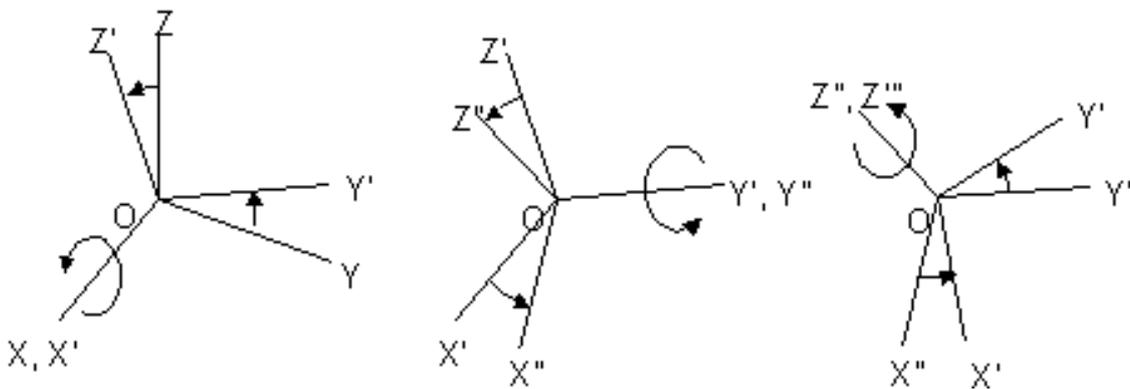
$$[R_{\text{med/lat}}] = \begin{bmatrix} C\alpha & 0 & -S\alpha \\ 0 & 1 & 0 \\ S\alpha & 0 & C\alpha \end{bmatrix} \quad [R_{\text{ant/pos}}] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & C\beta & S\beta \\ 0 & -S\beta & C\beta \end{bmatrix} \quad [R_{\text{vertical}}] = \begin{bmatrix} C\gamma & S\gamma & 0 \\ -S\gamma & C\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

where:

$C\alpha$ : cosine of the angle ( $\alpha$ ) through which the distal LCRS was first rotated.

$S\beta$ : sine of the angle ( $\beta$ ) for the second rotation, with similar definitions applying to the remaining terms.

**Figure 5.4:** Illustration of Euler angle convention employed



The successive rotations are arranged into a single transformation matrix according to the rules of matrix multiplication to give

$$[R]= \begin{bmatrix} C\alpha * C\gamma + S\alpha * S\beta * S\gamma & C\beta * S\gamma & -S\alpha * C\gamma + C\alpha * S\beta * S\gamma \\ -C\alpha * S\gamma + S\alpha * S\beta * C\gamma & C\beta * C\gamma & S\alpha * S\gamma + C\alpha * S\beta * C\gamma \\ S\alpha * C\beta & -S\beta & C\alpha * C\beta \end{bmatrix} \quad (\text{eq 5.7})$$

The cosine and sine of the angles  $\alpha$ ,  $\beta$  and  $\gamma$  are determined by the relative orientations of the proximal and distal LCRS's. Importantly, each LCRS is constructed from orthogonal unit vectors; therefore, the cosine and sine of the angles between the reference systems are determined by the following rotational transformation matrix.

$$[\text{RotationT}] = \begin{bmatrix} \mathbf{I}' \cdot \mathbf{I} & \mathbf{I}' \cdot \mathbf{J} & \mathbf{I}' \cdot \mathbf{K} \\ \mathbf{J}' \cdot \mathbf{I} & \mathbf{J}' \cdot \mathbf{J} & \mathbf{J}' \cdot \mathbf{K} \\ \mathbf{K}' \cdot \mathbf{I} & \mathbf{K}' \cdot \mathbf{J} & \mathbf{K}' \cdot \mathbf{K} \end{bmatrix} \quad (\text{eq 5.8})$$

where:

Vector components of the proximal LCRS are  $\mathbf{I}$ ,  $\mathbf{J}$  and  $\mathbf{K}$ .

Vector components of the distal LCRS are  $\mathbf{I}'$ ,  $\mathbf{J}'$  and  $\mathbf{K}'$ .

Each Euler angle is calculated using the following equations

$$\text{Angle } \beta \text{ (adduction)} = \arcsin(-\mathbf{K}' \cdot \mathbf{J}) \quad (\text{eq 5.9})$$

$$\text{Angle } \alpha \text{ (flexion)} = \arcsin\left(\frac{\mathbf{K}' \cdot \mathbf{I}}{\cos(\beta)}\right) \quad (\text{eq 5.10})$$

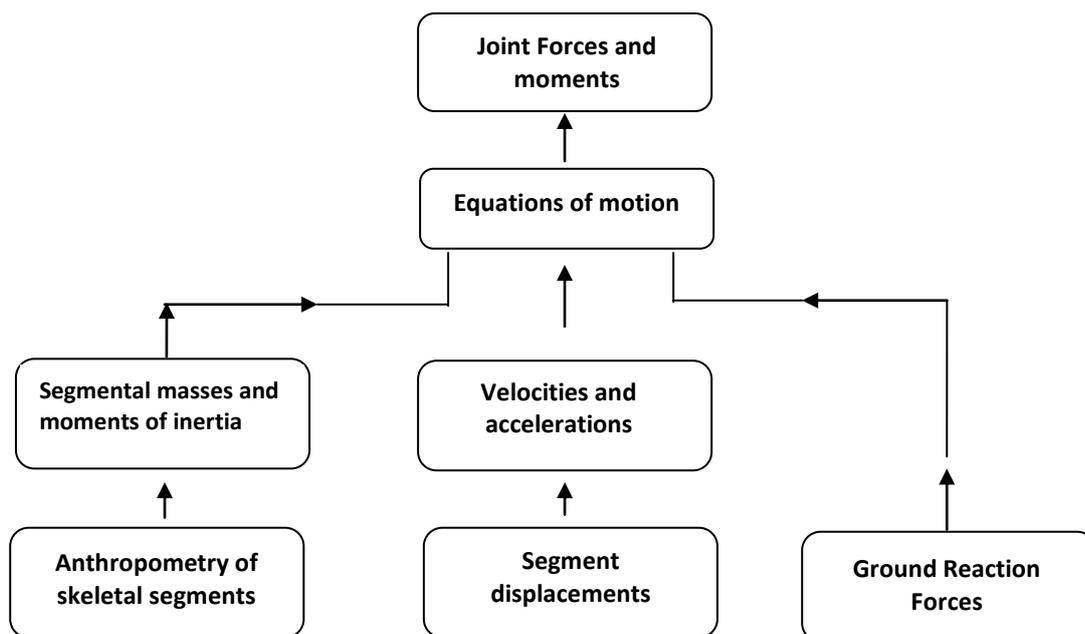
$$\text{Angle } \gamma \text{ (internal rotation)} = \arcsin\left(\frac{\mathbf{I}' \cdot \mathbf{J}}{\cos(\beta)}\right) \quad (\text{eq 5.11})$$

The extent to which joint angles calculated from the kinematic models correspond to true orientations of body segments is dependent upon how closely the LCRSs' coincide with the actual joint axes. Sensitivity analyses have illustrated non-uniformity in the magnitude of errors across the different joint angles. Flexion-extension angles are reported to be the most unaffected by perturbations in orientation of LCRS's (Kadaba, Ramakrishnan and Wooten 1990). In contrast, abduction-adduction angles are reported to be most affected, with the magnitude of errors influenced by the position of the segment around the flexion-extension axis (Kadaba, Ramakrishnan and Wooten 1990).

### 5.3 Kinetics

The fundamental goal for many biomechanical investigations of resistance training is to conduct kinetic analyses that give insight into the forces and torques that cause motion. Direct measurement of muscular forces is methodologically challenging and rarely attempted. Instead, the sum of individual forces and moments developed by muscles and structures such as ligaments are measured based on the inertial properties of the body and the resultant motion. The process of calculating forces and moments from the motion they create is referred to as inverse dynamics. Figure 5.5 provides a schematic account of the inverse dynamics approach.

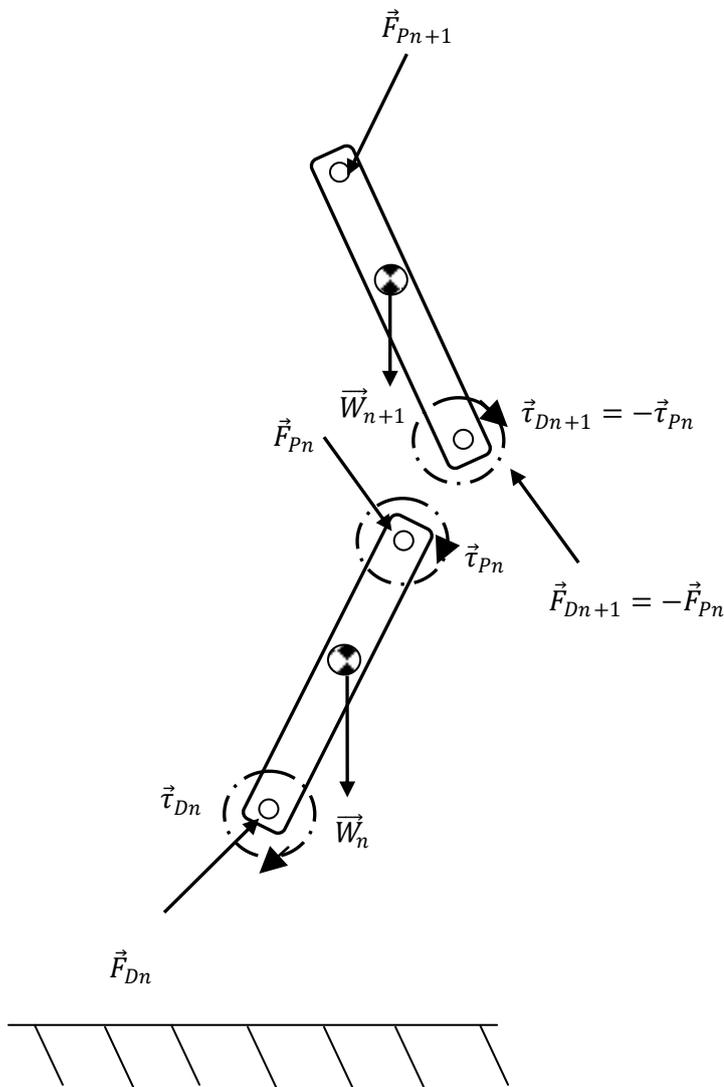
**Figure 5.5:** Schematic overview of the inverse dynamics approach



## Linked segment equations

To determine the net forces and moments acting on each segment, Newtonian and Euler equations of motion are employed, respectively. Figure 5.6 illustrate the approach used to calculate joint kinetics for the lower body. The process begins with the most distal segment (the foot) and continues proximally. Knowledge of the position and magnitude of the ground reaction force vector provides the input for the most distal segment. Based on the kinematic and segmental properties of the foot, the net force and moment at the proximal end of the joint can then be computed (see equations 5.12 and 5.13). Importantly, the connection of segments at a joint ensures that the adjacent segment experiences an equal but opposite force and moment. Based on this premise, the input for the next segment is created and the process can be promulgated up the kinetic chain. The net force and moment calculated at the proximal end of each joint are commonly referred to as the joint force and joint moment. These inter-segmental values are conceptual kinetic qualities that are unlikely to be present in any single anatomic structure (Crowninshield and Brand 1981). Rather, the values represent the summed effect of all structures that produce forces or moments across the joint (e.g. muscle forces, ligament forces, tendon forces, bone on bone forces). The reduction of individual forces and moments to a single net value may obscure important mechanical occurrences. However, the calculation of net joint forces and moments enable researchers to infer the magnitudes of muscular actions and overall stress placed on joints which are important factors for study of performance enhancement and injury prevention (Zajac and Gordon 1989).

**Figure 5.6:** Planar free body diagram illustrating the kinetics of a link-segment model used for inverse dynamics analysis



$\vec{F}_{Pn}$  = Joint force acting on the proximal aspect of the  $n^{\text{th}}$  segment.  $\vec{F}_{Dn}$  = Joint force acting on the proximal aspect of the  $n^{\text{th}}$  segment.  $\vec{F}_{Pn+1}$  = Joint force acting on the proximal aspect of the  $n^{\text{th}} + 1$  segment.  $\vec{F}_{Dn+1}$  = Joint force acting on the distal aspect of the  $n^{\text{th}} + 1$  segment.  $\vec{\tau}_{Pn}$  = Joint torque acting on the proximal aspect of the  $n^{\text{th}}$  segment.  $\vec{\tau}_{Dn}$  = joint torque acting on the proximal aspect of the  $n^{\text{th}}$  segment.  $\vec{\tau}_{Dn+1}$  = Joint torque acting on the distal aspect of the  $n^{\text{th}} + 1$  segment.  $\vec{W}_n$  = Weight of the  $n^{\text{th}}$  segment.  $\vec{W}_{n+1}$  = Weight of the  $n^{\text{th}} + 1$  segment.

### Calculation of net joint forces

From Newton's second law ( $\vec{F}_{net} = m\vec{a}$ ), proximal and distal forces can be calculated from

$$\vec{F}_{Pn} + \vec{F}_{Dn} + \vec{W}_n = m\vec{a}_n \quad (\text{eq 5.12})$$

where:

- $\vec{F}_{Dn}$ : net force vector applied distally to segment n
- $\vec{F}_{Pn}$ : net force vector applied to the proximal joint centre of segment n
- $\vec{W}_n$ : force of gravity applied to the COM of segment n
- $m\vec{a}_n$ : mass of segment n multiplied by the linear acceleration of segment n

$-\vec{F}_{Pn}$  becomes  $\vec{F}_{dn+1}$  to recursively generate a solvable equation of motion for the proximal joint force of the successive segment (n+1)

### Calculation of net joint moments

From Euler's angular equation of motion ( $\vec{\tau}_{net} = I\vec{\alpha}$ ), proximal and distal moments can be calculated from

$$\vec{\tau}_{Pn} + \vec{\tau}_{Dn} + \vec{W}_n + (\vec{p}_{CGpn} \times \vec{F}_{Pn}) + (\vec{p}_{CGDn} \times \vec{F}_{Dn}) = I\vec{\alpha}_n \quad (\text{eq 5.13})$$

where:

- $\vec{\tau}_{Dn}$ : net moment applied distally to segment n
- $\vec{\tau}_{Pn}$ : net moment applied to the proximal joint centre of segment n
- $\vec{W}_n$ : force of gravity applied to the COM of segment n
- $\vec{F}_{Dn}$ : net force vector applied distally to segment n
- $\vec{F}_{Pn}$ : net force vector applied to the proximal joint centre of segment n
- $\vec{p}_{CGDn}$ : position vector from segment n COM to distal joint force
- $\vec{p}_{CGpn}$ : position vector from segment n COM to proximal joint force
- $I\vec{\alpha}_n$ : moment of inertia of segment n multiplied by the angular acceleration of segment

$-\vec{\tau}_{Pn}$  becomes  $\vec{\tau}_{Dn+1}$  to recursively generate a solvable equation of motion for the proximal joint moment of the successive segment (n+1).

## 5.4 Model Evaluation

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Linked segment kinematic and kinetic models have been employed consistently over the last three decades to investigate various resistance training practices (Cholewicki, McGill and Norman 1991, McLaughlin, Lardner and Dillman 1978, Brown and Abani 1985, Flanagan and Salem 2008). Escamilla et al. (2000) were among the first to demonstrate the limitations of 2D analyses and the need to employ 3D kinematic and kinetic models when attempting to accurately quantify biomechanical parameters during performance of resistance exercises. The magnitude of errors imposed during 2D analyses was shown to increase as segmental displacements progressively deviated from a single plane (Escamilla et al. 2000). However, even with the use 3D methods, there are numerous sources of error that can affect the accuracy and validity of linked segment models. Known sources of error include: location of joint centres and segment centres of mass; estimation of segment mass and moment of inertia; measurement and translation of external forces to the model; movement between surface markers and the underlying bone; calculation of linear and angular accelerations; and deformation of segments (Plamondon, Gagnon and Desjardins 1996). Research studies investigating the validity of linked segment models have employed a range of methodological approaches. Most frequently, validity and error sources have been assessed by comparing joint kinetics calculated when progressing from proximal to distal segments (top-down) with the same variables calculated using the opposite progression (bottom-up). Kinetic values calculated at the lumbar spine using both approaches have exhibited very strong correlation values (Plamondon, Gagnon and Desjardins 1996, Kingma et al. 1996). In addition, multiple studies have reported strong agreement of kinetic values with differences generally as low as 5 to 15% (Kingma et al. 1996, Potvin, Ball, et al. 1988). The speed of movement has been shown to influence the magnitude of discrepancies between top-down and bottom-up models, thereby confirming that a proportion of the error inherent to linked segment models is due to inaccuracies in determining segment accelerations (Plamondon, Gagnon and Desjardins 1996). Studies investigating the validity of linked segment models have also employed sensitivity analyses as a means of assessment. The advantage of this strategy is that different model inputs can be varied systematically to measure change in outputs, with the implication that ill-conditioned models where small perturbations result in large changes are not valid. Previous studies have conducted sensitivity analyses with systematic variations in location of joint centres (Desjardins, Plamondon and Gagnon 1998) segment parameters (Lariviere and Gagnon 1999), joint axes (Kadaba, Ramakrishnan and Wooten 1990), segment accelerations (Desjardins, Plamondon and Gagnon 1998), and centre of pressure location

(Plamondon, Gagnon and Desjardins 1996). The results have shown that linked segment models are generally well conditioned and robust to small changes in input values. The effect of small errors has been shown to depend upon the model used and the movement investigated (Desjardins, Plamondon and Gagnon 1998). Bottom-up models that incorporate force platforms to provide accurate measurement of the external forces applied to the system have been shown to be more robust than top-down models (Desjardins, Plamondon and Gagnon 1998). However, in analyses similar to the current project where very large external ground reaction forces are created, small errors in translation of forces to the coordinate system of the foot segment can result in relatively large errors which are promulgated up the kinetic chain (Kingma et al. 1996). Careful experimental setup including calibration of force platforms and accurate marker placements of the foot segment are recommended to limit this source of error (Kingma et al. 1996).

An important consideration for the accuracy of the biomechanical model employed in the current project is the calculation of body segment parameters. The values are estimated using proportional anthropometric regression equations which require simple measurements such as height and mass (Dempster 1955). However, these simple measurements cannot account entirely for the variability in body segment parameters. In addition, the regression equations were developed from cadaveric specimens of slender males. In contrast, the participants of the current project ranged from moderate to extremely hypertrophied. To investigate the effect of employing normative based values for segmental parameters of hypertrophied males, Chiu and Salem (2006) compared the kinetics calculated from normative and subject specific data during performance of the power clean. Subject specific data were determined using whole body DEXA scanning. The greatest differences between normative and subject specific parameters were obtained for the thigh and leg segments. In both cases, the use of normative data resulted in underestimations of segment mass. Based on the inverse dynamic equations, these errors resulted in overestimations of net joint forces and subsequently overestimations of net joint moments. The magnitude of kinetic errors obtained when using normative data were largest during phases of the movement where acceleration of the shank and femur were at their largest. However, despite the clear systematic nature of errors introduced, the relative magnitudes were low, with differences in the region of 0.6 to 1.6% of the values obtained when using subject-specific parameters. As a result of the considerable expense required to develop subject specific data and its minimal effect on the estimation of kinetic values, the use of normative based parameters is considered appropriate for this project.

## 5.5 Summary and Conclusion

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The link segment model selected for the current project enables the collection of kinematic and kinetic variables that provide useful information on the movement strategies employed and subsequent internal stresses created when performing resistance exercises. This information is combined with additional biomechanical data in subsequent chapters to assess the mechanical stimulus presented by those contemporary training practices that have been selected for analysis. The specific model used to collect internal variables has been extensively trialled in research studies examining gait, manual lifting and resistance training. The research base has established that the model is robust to small errors in inputs and provides an appropriate balance between model complexity and validity of inherent assumptions. For the purposes of the current project, the biomechanical model is included in studies that feature repeated measures designs where participants serve as their own control. These research designs limit the impact of errors on study conclusions due to reduced variability between conditions. In addition, by collecting data in a single testing session using the same calibration settings and marker placements, errors between resistance practices are minimised, thereby assisting in the ability to detect differences in biomechanical variables where they exist.

## CHAPTER 6. EFFECTS OF MOVEMENT VELOCITY

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### 6.1 Prelude

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Perhaps the most substantive conceptual development in the contemporary training of powerlifters is their performance of fast velocity repetitions with sub-maximum loads. Traditionally, the training practices of powerlifters have focused almost exclusively on the use of heavy loads performed with relatively slow velocities. As reported in chapter three, the majority of powerlifters now believe there are biomechanical and neurophysiological advantages to performing exercises such as the squat, bench press and deadlift as fast as possible. Among these proposed advantages include the improvement of muscular power, which is considered one of the most important fitness variables for determining success in many sports. However, some researchers have argued that performance of fast velocity repetitions should be restricted to exercises (e.g. clean, snatch, jump squat and bench throw) that exhibit specific mechanical profiles. In general, the squat, bench press and deadlift are believed to exhibit profiles that are incompatible with the development of high velocities and therefore unlikely to improve muscular power. There is, however, limited evidence to support this conclusion. The purposes of this chapter are twofold, firstly, to investigate the biomechanical stimulus created when a standard powerlifting exercise is performed as fast as possible using a range of sub-maximum loads. Secondly, this chapter seeks to assess the potential for this training practice to develop muscular power. To achieve this latter aim, the biomechanical stimulus of the powerlifting exercise will be compared with the power clean, an exercise commonly prescribed to develop muscular power.

## 6.2 Introduction

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The importance of movement velocity as a variable which can influence adaptations to chronic resistance training has only recently been acknowledged. Traditionally, prescription of resistance training for health or performance improvements omitted guidelines for movement velocity (Feigenbaum and Pollock 1999) or provided vague recommendations, suggesting that 'controlled' or 'moderate' velocities be used (Hass, Feigenbaum and Franklin 2001, Pereira and Gomes 2003). Ambiguity in previous guidelines reflects the paucity of research that was available at the time. Studies investigating the effects of movement velocity on acute and chronic resistance training performance were initially conducted using isokinetic and hydraulic equipment (Pereira and Gomes 2003). Isokinetic devices were selected as they enabled researchers to precisely control the velocity of simple uni-joint movements. However, limitations exist for very fast velocities where only a small portion of the movement is isokinetic due to relatively large amplitudes of the acceleration and deceleration phases (Gleeson and Mercer 1996). Hydraulic devices were also investigated due to their potential to modify resistance based on the input velocity provided, although, in contrast to isokinetic technology, the devices are unable to constrain movement to a constant velocity.

The majority of studies investigating Isokinetic training at slow speeds (20 to 99°/s) reported significant improvements in torque production across a wide range of testing velocities, with some general trends indicating that the magnitude of improvements were greatest near those used in training (Caiozzo, Perrine and Edgerton 1981, Pipes and Wilmore 1975, Moffroid and Whipple 1970). Results from isokinetic studies of fast speeds (100 to 300°/s) are more varied, with some studies reporting improvements in torque production across a range of velocities (Pipes and Wilmore 1975, Coyle et al. 1981, Timm 1987) and others demonstrating that improvements were limited to fast velocities (Caiozzo, Perrine and Edgerton 1981, Ewing et al. 1990). Inconsistencies in results could be due to a range of methodological factors including training velocities used and tested, the resistance training program followed (i.e. training frequency, number of sets, repetitions and rest periods allocated), and the data collection procedures employed. Overall, the results from isokinetic studies suggest that a degree of velocity-specificity may exist; however, improvements of varying magnitude can generally be obtained at velocities above and below that used in training.

Results from studies incorporating hydraulic machines have been more varied than those using isokinetic devices. No general trends have emerged with approximately an equal number of studies reporting generality in adaptations (Petersen et al. 1989, Petersen, Miller and Wenger 1984) and others reporting improvements specific to the velocities used in training (Bell et al. 1992, Aagaard et al. 1996). Similar methodological limitations apparent in isokinetic studies also apply for research conducted using hydraulic equipment. On the basis of these initial studies it is unsurprising that prescriptions of resistance training were previously limited in terms of guidelines for movement velocity.

More recently, research investigating the effects of movement velocity on resistance training adaptations has featured isoinertial loading. It is clear from the relatively simple mechanics of isoinertial loads (in comparison with that created by isokinetic devices), that movement velocity is determined by neural drive and the subsequent impulse applied by the musculoskeletal system as well as the magnitude of the resistance. With very light resistances an individual can choose to lift the load with a variety of acceleration profiles resulting in slow to fast velocity movements. However, as the resistance increases, the maximum velocity that can be obtained is reduced, irrespective of the intention of the individual (Cronin, McNair and Marshall 2003). Delineation between intended movement velocity and actual movement velocity has led to two conflicting theories regarding adaptations to resistance training (Cormie, McGuigan and Newton 2011). The first theory, which received conflicting results from isokinetic and hydraulic studies, postulates that physiological adaptations are not influenced by individuals' intentions and instead are dependent upon the actual movement velocity generated. The opposing theory contends that the ability to produce high forces during fast velocity repetitions can be enhanced irrespective of the actual movement velocity produced, provided there is intention to move as fast as possible.

Investigations comparing purposeful fast and slow movements using the same external resistance are unable to provide support for the theory of intention as there is no means to discern whether adaptations are due to the movement velocity or the intention behind them (Cormie, McGuigan and Newton 2011). The strongest piece of evidence supporting the theory of intention includes the findings from the frequently cited research of Behm and Sale (1993). The authors recruited male and female physical education students to a training intervention where the dorsiflexor muscles of each leg were stimulated unilaterally with different regimes of work. With one foot the participants performed fast velocity (300°/s)

ankle flexions, and with the other only isometric actions were permitted. For both muscle actions participants were instructed to attempt to displace the load as fast as possible. The results of the study demonstrated that muscles from both legs adapted similarly and exhibited significant improvements in torque production during high velocity movements. In addition, similar changes to isometric force-time characteristics were reported for the muscles of each leg during voluntary and evoked actions. The authors hypothesised that similar temporal force characteristics and high rates of neural activation produced during both isometric and high velocity muscle actions were responsible for the equivalent adaptations (Behm and Sale 1993). Unfortunately, similar research designs have not been conducted with more complex movements and better trained participants. However, on the basis of the results generated by Behm and Sale (1993) and the face validity of the approach, it is now commonly recommended that athletes should attempt to lift loads as fast as possible when seeking to develop muscular power or the ability to produce large forces during high velocity actions (American College of Sports Medicine 2009, Newton and Kraemer 1994).

The terminology used to identify the practice of lifting loads as fast as possible is varied and largely inconsistent. The most popular and general expression used by researchers is explosive resistance training (ERT) (American College of Sports Medicine 2009, McBride et al. 2002, Newton and Kraemer 1994). Depending upon the exercises included, researchers may also use the expression ballistic training (Kraemer and Fleck 2004). In contrast, popular terminology used by practitioners includes speed repetitions, compensatory acceleration and the maximum dynamic method (Jones et al. 1999, Zatsiorsky 1995, Cressey et al. 2007). For the purposes of this thesis, ERT which is the most general and encompassing of the terminologies will be used.

At present, the practice of ERT is recommended for athletes by two of the largest professional bodies in strength and conditioning (American College of Sports Medicine 2009, Baechle and Earle 2008); however, there are aspects of the training practice that are not well understood and require further investigation. In particular, research to determine which exercises are best incorporated with ERT is warranted. To increase the likelihood of adaptations transferring to sports performance it is recommended that exercises performed explosively should involve muscular action across multiple joints and create large power outputs (Kraemer and Fleck 2004). Exercises that can meet these criteria are conventionally grouped into four categories: 1) plyometric; 2) traditional; 3) ballistic; and 4)

weightlifting (Cormie, McGuigan and Newton 2011). Plyometric exercises are characterised by rapid SSC muscle actions and are typically performed with minimal or no external resistance. Musculature of the upper and lower body can be targeted with a range of plyometric medicine ball throws and jumping variations, respectively. Despite minimal or no external loading the vertical forces and net joint moments created during plyometric exercises can be extremely large and comparable to exercises performed with significantly greater external resistance (Bobbert, Huijing and van Ingen Schenau 1987). The primary advantage of plyometric exercises is the high degree of specificity that can be obtained with many sporting movements. However, for some researchers plyometrics are considered distinct from the practice of ERT due to the reduced external loading and rapid SSC muscle actions which are believed to present divergent physiological and biomechanical stimuli compared with the other types of resistance exercises (Cormie, McGuigan and Newton 2011). In particular, plyometric exercises are considered to make greater use of the stretch reflex and proprioceptive structures, whilst creating unique force-time characteristics (Siff 2003).

The category of traditional resistance exercises comprises a wide range of movements that are currently recommended for ERT by powerlifters and are the focus of this chapter. The term traditional is made in reference to the use of these exercises in the 1960s when resistance training was first adopted by athletes such as American football players to improve performance. The squat, bench press and deadlift are the standard movements that have come to characterise traditional resistance exercises. However, more recently, the terminology has been used to characterise resistance exercises that are considered distinct from ballistic and weightlifting movements based on the need to reduce the system velocity to zero at the end of the propulsive phase (Kraemer and Fleck 2004). That is, with traditional resistance exercises such as the squat, the load can be lifted as fast as possible during the initial stages of the concentric movement but must be decelerated so that at full extension the barbell-lifter system is motionless. In contrast, during the jump squat which is considered a ballistic movement, the load and body can be positively accelerated throughout the concentric phase and projected from the ground (Newton and Kraemer 1994). It is primarily as a result of the need to decelerate the system during traditional resistance exercises that the majority of researchers in strength and conditioning recommend that ERT should not be performed with these movements (American College of Sports Medicine 2009, Newton and Kraemer 1994, Cormie, McGuigan and Newton 2011). Interestingly, prior to the recent popularisation of ERT, an influential powerlifting champion promoted the use of performing traditional resistance exercises as fast as possible to

increase strength, power and athleticism (Hatfield 1982). The training practice was identified as compensatory acceleration and was subsequently investigated by Jones et al. (1999). The authors compared maximum strength and power increases over a fourteen week intervention period with college American football players. The participants were randomly allocated to the control or experimental condition. Both groups performed the same training regime for the bench press with the exception that those in the control condition performed each repetition at a sub-maximum velocity while those in the experimental condition performed each repetition as fast as possible. Both training groups improved their 1RM bench press and seated medicine ball throw, with significantly greater improvements obtained by those in the experimental condition (+9.9 kg vs. +5.0 kg, and +0.7 m vs. +0.3 m, respectively). The results demonstrate that performing ERT with traditional resistance exercises can improve performance related tests of strength and muscular power in well trained athletes, and may also produce superior results to standard resistance training practices. The findings of Jones et al. (1999) seemingly contradict the position of many researchers that traditional resistance exercises are not suitable for ERT. However, the research was restricted to the bench press, which is an exercise that may have limited transfer to most sporting movements. In addition, the study does not address whether better results may have been obtained if the training was performed with ballistic or weightlifting movements as is recommended.

The first study to compare the effects of resistance training programs comprised of traditional resistance exercises or weightlifting movements was conducted by Hoffman et al. (2004). Twenty members of a college American football team were position matched and separated into one of the training conditions. At the completion of the fifteen week intervention both groups improved their maximum strength, forty yard sprint speed and agility performance. The results indicated that group differences existed with those performing weightlifting exercises demonstrating significantly greater improvements in vertical jump and trends towards greater improvements in lower body maximum strength and speed. The results presented by Hoffman et al. (2004) have been used as evidence to support the position that weightlifting exercises are superior for athletic development. However, the study by Hoffman et al. (2004) was conceptualised as a comparison of traditional views of powerlifting training versus the methods used by Olympic weightlifters. As a result, the group performing the traditional resistance exercises did not attempt to perform repetitions as fast as possible, thereby making it difficult to establish whether the results were caused by the exercises used or the method by which they were performed. Future studies that seek to determine if powerlifting or weightlifting practices are more

effective for athletes should ensure that all repetitions are performed with the intent to lift the load as fast as possible to remove this potential confounding factor.

Within current research paradigms it is to be expected that any future studies comparing powerlifting and weightlifting training would employ the same relative resistances and attempt to equate the overall volume of training to ensure these factors do not influence the result. However, at present it is not clear how factors such as the external resistance influence the stimulus of traditional resistance exercises performed explosively, making it unclear whether a comparison using the same relative loads is appropriate. The powerlifters interviewed for the current project used a wide range of exercises and loads when performing ERT with the belief that different combinations provided distinct stimuli and adaptations. In contrast, previous research investigating the biomechanical stimulus of traditional resistance exercises performed explosively has been limited, with studies focusing on the bench press across a narrow range of loads (Elliott, Wilson and Kerr 1989, Lander et al. 1985). In addition, the variables analysed have been restricted to external variables such as the ground reaction force and velocity of the barbell, which provide no information regarding movement strategies and distribution of internal stresses. As a necessary first step to characterise the biomechanical stimulus created with traditional resistance exercises performed explosively a more complete biomechanical investigation must be completed. This is the purpose of this chapter, with the deadlift selected for analysis due to its popularity and rapid extension of the lower body joints which is characteristic of many sporting movements. To assess the potential effectiveness of the training practice to develop muscular power the biomechanical stimulus of the power clean was also measured to provide a comparison. The power clean is considered by many researchers and practitioners in strength and conditioning to be the “gold standard” exercise for developing power and also features similarities in gross movement pattern with the deadlift (Chiu, Moore and Favre 2007, Stone et al. 2006).

## 6.3 Methods

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### Experimental Approach to the Problem

A cross-sectional, repeated measures design was used to quantify and compare kinematics and kinetics of the deadlift performed at maximum and sub-maximum velocities, and the power clean performed at maximum velocity only. The experimental approach provided original information regarding the mechanical stimulus of a traditional resistance exercise as it was progressed from its standard use at sub-maximum velocity to implementation within an ERT framework. Comparisons between maximum velocity deadlifts and power cleans were included to assess the validity of claims by researchers that traditional resistance exercises are not suited for ERT. A range of internal and external biomechanical variables were collected to assess the output of the exercise and the internal stresses created at different segments of the body. Data were collected for each participant over two sessions separated by one week. Session one was performed in the gymnasium and involved one-repetition maximum (1RM) testing in the deadlift and power clean. Session two was performed in the laboratory where participants performed repetitions for each condition using loads of 40, 60 and 80% of their recorded 1RM. Kinematics and kinetics were analysed during the second session only. Multiple loads were used in the same testing session to maximise reliability of comparisons (i.e. with regard to factors such as marker placement and current physiological status). The testing sessions were extensively piloted to ensure that confounding effects of fatigue were minimised.

### Participants

Twelve male strongman athletes participated in the study (age:  $27.4 \pm 4.5$  yr; stature:  $182.5 \pm 3.3$  cm; mass:  $112.1 \pm 19.2$  kg; resistance training experience:  $11.7 \pm 4.4$  yr). Participants were recruited from heavyweight and under 105 kg Scottish strongman competitions. Variations of the deadlift and power clean are regularly included in strongman competitions and each participant had a minimum of two years regular training experience with each exercise. Participants were notified about the potential risks involved and gave their written informed consent to be included. Prior approval was given by the ethical review panel at Robert Gordon University, Aberdeen, UK.

## **1RM Testing**

All participants were experienced in performing 1RM tests in the deadlift and power clean and could predict their maximum strength accurately. Based on a predicted 1RM load participants performed a series of warm-up sets and up to 5 maximum attempts. A minimum of 2 minutes and a maximum of 4 minutes recovery time were allocated between attempts. Within this time frame participants chose to perform the lift based on their own perception of when they had recovered. No supportive aids beyond the use of a weightlifting belt were permitted during the tests. Both exercises were initiated with the barbell resting on the floor. Participants were instructed to catch the barbell during the power clean in a “quarter squat” position. Any attempt which was received in a full squat position with upper thighs parallel to the floor was ruled unsuccessful (Kawamori et al. 2005). Deadlifts were performed with a conventional shoulder width stance and deemed to be successful if the barbell was not lowered at any point during the ascent and upon completion of the movement the body posture was erect, the knees were straightened and shoulders retracted. The order of 1RM tests were randomised with a 30 minute rest period allocated for recovery between exercises.

## **Sub-maximum Load Testing**

Prior to performing maximum speed repetitions participants engaged in their own specific warm-up. Generally, this began with two to four sets of the deadlift and power clean with a light load (e.g. < 40% 1RM) for 6 to 10 repetitions. Participants then began to perform repetitions at maximum speed with progressively heavier loads. Once participants were suitably prepared, data were collected initially with the sub-maximum velocity deadlifts performed with 40, 60 and 80% 1RM in ascending order. Participants were instructed to perform the repetitions at a moderate speed indicative of training used to develop muscular hypertrophy. Once completed, participants then performed maximum velocity deadlifts and power cleans with the same relative loads (i.e. 40–80% 1RM) in a randomised order. Trials were randomly presented to minimise the confounding effects of fatigue and potentiation. One trial comprising two repetitions was performed for each load and condition to assess intra-trial reliability. A minimum two minute rest period was allocated between trials with a longer rest period of up to four minutes made available if the participant felt it necessary to produce a maximum performance. Instructions were given at the beginning of each trial to perform the concentric portion of each repetition with maximum effort attempting to lift the load as fast as possible whilst maintaining contact with the ground throughout the deadlift.

For each trial the repetition that produced the greatest peak barbell velocity was selected for further analysis.

### **Biomechanical Analyses**

The sub-maximum load trials were performed with a separate piezoelectric force platform (Kistler, Type 9281B Kistler Instruments, Winterthur, Switzerland) under each foot, in a capture area defined by a seven-camera motion analysis system (Vicon MX, Vicon Motion Systems, Oxford, UK). Marker position and ground reaction force data were captured at 200 and 1200 Hz respectively. Based on a frequency content analysis of the three-dimensional coordinate data, marker trajectories were filtered using a digital fourth-order low-pass Butterworth filter with a cut-off frequency of 6 Hz. Internal kinematics and kinetics were calculated using the models presented in chapter five. Instantaneous velocities and accelerations were calculated by numerical differentiation of the position data (Hildebrand 1974). Kinematic and kinetic measures for the hip, knee and ankle were calculated for both left and right sides and averaged to obtain single values. The starting point for each trial was defined as the point where the centre of the barbell was raised 2 mm vertically above its initial resting height. The end of each trial was defined as the point where the centre of the barbell reached maximum vertical elevation. The increment of 2 mm was selected because force application at the beginning of the movement caused the barbell to oscillate and generate additional noise to the positional data. Pilot testing revealed that the selected cut-off was the smallest value consistently greater than the magnitude of the added noise. Instantaneous external power values were calculated as the product of the vertical ground reaction force and corresponding barbell vertical velocity. Power values were also measured at the level of the joint by taking the product of the flexion-extension net joint moment and flexion-extension angular velocity. The moment arm of the resistance was found by calculating the horizontal distance from the centre of the barbell to the relevant joint centre.

## **Statistical Analyses**

Intra-trial reliability for each variable analysed was assessed by intraclass correlation coefficient (ICC). As recommended by Baumgartner (2006), ICCs were calculated with a correction factor for number of repetitions performed per trial ( $n = 2$ ) and number of repetitions used in the criterion score ( $n = 1$ ). Intra-trial reliability for all variables reported were high with values ranging from 0.88 to 0.98. Two distinct sets of analyses were made to compare: a) the effect of repetition velocity (sub-maximum vs. maximum velocity deadlifts); and b) the effect of exercise (power clean vs. deadlift, both at maximum velocity). In both sets of analyses, potential differences in kinematics and kinetics were investigated using a 2x3 (condition x load) repeated measures ANOVA. Significant main effects were further analysed with Bonferroni adjusted pair-wise comparisons. Statistical significance was set at  $p < 0.05$ . All statistical procedures were performed using the SPSS software package (SPSS, Version 17.0, SPSS Inc., Chicago, IL).

## 6.4 Results

### Effect of repetition velocity

As the magnitude of the external resistance increased, the time taken to complete repetitions in both sub-maximum and maximum velocity deadlifts increased also. Repetition duration, vertical barbell displacement and velocity values across loads are presented in Table 6.1. The data show that during maximum velocity deadlifts the barbell was consistently elevated to a greater height and that average and peak velocity values were significantly greater than those obtained during the control repetitions.

**Table 6.1:** Displacement and velocity characteristics of maximum and sub-maximum velocity deadlifts (mean±SD)

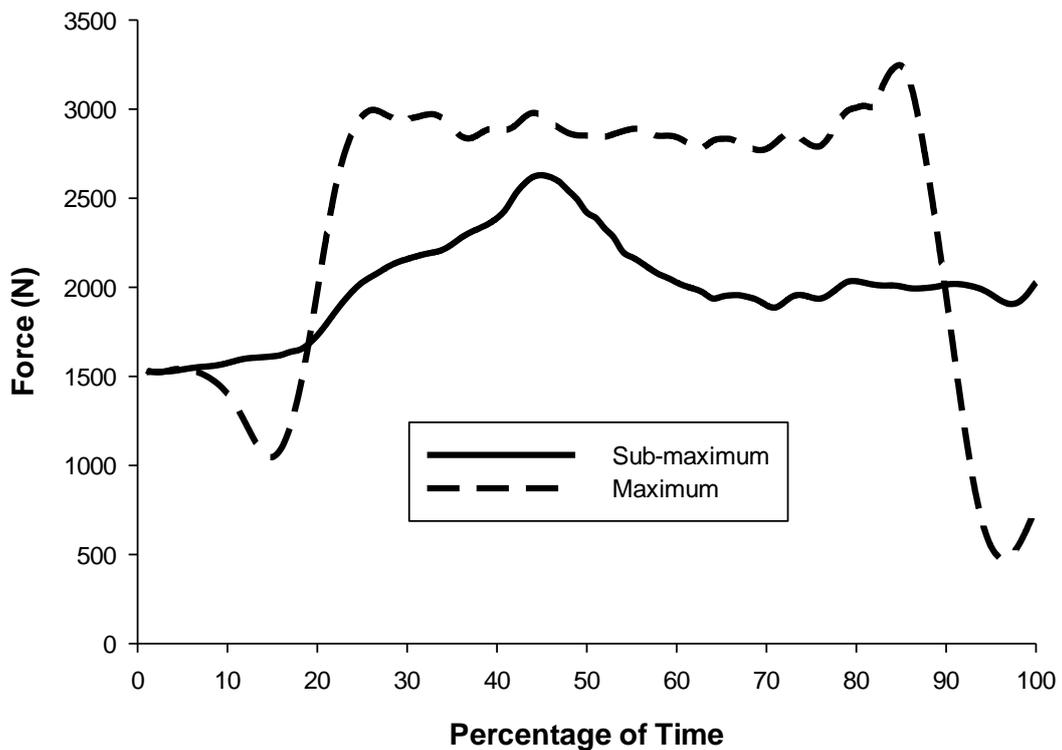
|                                      | Sub-maximum deadlift |             |             | Maximum deadlift |             |              |
|--------------------------------------|----------------------|-------------|-------------|------------------|-------------|--------------|
|                                      | 40% 1RM              | 60% 1RM     | 80% 1RM     | 40% 1RM          | 60% 1RM     | 80% 1RM      |
| Repetition duration (s)              | 1.54 ± .23*          | 1.65 ± .21* | 1.97 ± .19* | 0.67 ± .05       | 0.84 ± .10  | 1.44 ± .23   |
| Displacement (m)                     | 0.62 ± .07           | 0.59 ± .07  | 0.55 ± .04  | 0.78 ± .08*      | 0.72 ± .09* | 0.65 ± .05*  |
| Average velocity (ms <sup>-1</sup> ) | 0.41 ± .19           | 0.36 ± .16  | 0.28 ± .10  | 1.15 ± .13*      | 0.88 ± .14* | 0.45 ± .06*  |
| Peak velocity (ms <sup>-1</sup> )    | 1.01 ± .24           | 0.80 ± .22  | 0.60 ± .11  | 1.81 ± .22*      | 1.33 ± .21* | 0.77 ± 0.09* |

\*Significantly greater than corresponding condition (p<0.05).

Distinct force-time profiles were obtained for maximum and sub-maximum velocity deadlifts. Figure 6.1 illustrates representative curves for the different conditions. These were produced by resampling the individual data sets by approximating values with a polynomial function (maximum 6<sup>th</sup> order) over an integer domain consisting of 500 data points, and then averaging values for the group. The curve representing the sub-maximum condition shows that RFD during the initial phase of the movement is low and that once peak force is obtained there is a gradual decrease to a lower level where values remain stable until the end of the movement. In contrast, with maximum velocity deadlifts there is an initial decrease in force, then rapid rise in values to a peak where values remain relatively stable

until the end phase of the movement where force quickly falls towards zero.

**Figure 6.1:** Representative force-time curves of maximum and sub-maximum velocity deadlifts



In addition to differences in force production, significant main effects of repetition velocity were also obtained for orientation of the hip and knee at the start of the movement. Significant Interaction effects of velocity and load revealed that differences in orientation of the hip and knee were greatest at the lightest load and failed to reach significance at the heaviest load. The results showed that participants initiated sub-maximum velocity deadlifts with increased hip and knee flexion angles (Table 6.2).

**Table 6.2:** Sagittal angles of maximum and sub-maximum velocity deadlifts at the start of movement (mean±SD)

|                 | Sub-maximum deadlift |              |             | Maximum deadlift |             |             |
|-----------------|----------------------|--------------|-------------|------------------|-------------|-------------|
|                 | 40% 1RM              | 60% 1RM      | 80% 1RM     | 40% 1RM          | 60% 1RM     | 80% 1RM     |
| Torso flex/ext° | 48.8 ± 9.5           | 51.9 ± 12.3  | 57.6 ± 12.9 | 55.8 ± 10.0*     | 56.2 ± 11.2 | 59.6 ± 13.3 |
| Hip flex/ext°   | 97.6 ± 6.2*          | 94.8 ± 6.4*  | 92.9 ± 6.4  | 90.3 ± 7.1       | 89.6 ± 7.0  | 92.7 ± 7.0  |
| Knee flex/ext°  | 86.3 ± 10.9*         | 81.8 ± 10.5* | 74.9 ± 9.9  | 71.7 ± 10.2      | 70.6 ± 9.4  | 70.5 ± 9.6  |
| Ankle flex/ext° | 25.4 ± 4.1           | 21.3 ± 4.1   | 22.8 ± 3.6  | 22.3 ± 3.8       | 21.7 ± 4.7  | 23.2 ± 4.6  |

\*Significantly greater than corresponding condition (p<0.05).

The increased velocity obtained when performing repetitions as fast as possible was achieved by significant increases in angular velocity of the torso, hip, knee and ankle. For the lightest loads peak and average joint velocities were up to 4 times faster for the maximum effort condition and up to 1.5 times faster when lifting the heaviest load.

Significant main and interaction effects of load and repetition velocity were also obtained for joint moments and joint powers. The interaction effects revealed that joint moments and powers were augmented during maximum velocity repetitions with the magnitude of the difference greatest when the external resistance was low. As the external resistance increased, values still remained significantly greater during maximum velocity repetitions compared with sub-maximum repetitions, however, the magnitude of the difference decreased. Increases in joint moments and powers during maximum velocity deadlifts were similar for the torso, hip and knee, with the greatest increases obtained at the ankle.

### **Deadlift and Power Clean Comparison**

The athletes were able to lift twice as much in the deadlift as compared with the power clean (1RM deadlift: 280.9 ± 48.8 kg; 1RM power clean: 139.2 ± 19.4 kg). Therefore, as expected, the greater absolute loads lifted during the deadlift resulted in significant main effects for GRF and velocity of the barbell (Table 6.3). The relative increases in force obtained with the deadlift were considerably less than the relative reductions experienced in velocity of the barbell. As a result, the external power values calculated during the power clean were significantly greater than those produced during the deadlift (Table 6.3).

**Table 6.3:** Comparison of force, velocity and power data obtained during the power clean and deadlift (mean±SD)

|                                      | Power Clean |             |             | Maximum deadlift |             |             |
|--------------------------------------|-------------|-------------|-------------|------------------|-------------|-------------|
|                                      | 40% 1RM     | 60% 1RM     | 80% 1RM     | 40% 1RM          | 60% 1RM     | 80% 1RM     |
| Average Force (kN)                   | 1.51 ± .23  | 1.70 ± .21  | 1.91 ± .23  | 1.97 ± .29*      | 2.45 ± .32* | 2.88 ± .39* |
| Peak Force (kN)                      | 2.40 ± .47  | 2.69 ± .39  | 2.86 ± .29  | 2.66 ± .40*      | 2.98 ± .46* | 3.23 ± .48* |
| Average velocity (ms <sup>-1</sup> ) | 1.64 ± .10* | 1.44 ± .19* | 1.28 ± .14* | 1.00 ± .13       | 0.69 ± .14  | 0.35 ± .06  |
| Peak velocity (ms <sup>-1</sup> )    | 2.72 ± .22* | 2.46 ± .38* | 2.01 ± .28* | 1.61 ± .22       | 1.11 ± .21  | 0.57 ± .09  |
| Average Power (kW)                   | 2.20 ± .38  | 2.19 ± .34* | 2.18 ± .33* | 1.93 ± .27       | 1.66 ± .29  | 0.95 ± .12  |
| Peak Power (kW)                      | 4.78 ± .61* | 4.94 ± .71* | 4.66 ± .48* | 4.05 ± .62       | 3.16 ± .62  | 1.79 ± .23  |

\*Significantly greater than corresponding condition (p<0.05).

In addition to differences obtained in discrete force values (average and peak), the overall profile of force-time curves for the deadlift and power clean were found to be distinct. Figure 6.2 illustrates representative force-time curves for each exercise. During the initial stage of the power clean total force and RFD was less than that developed for the deadlift. During the middle stages of the power clean force quickly dropped to zero before increasing rapidly to a second peak. The bimodal force profile developed during the power clean had a significant effect on PRFD with values consistently five times greater than that produced during the deadlift across all loads.

**Figure 6.2:** Representative force-time curves of the power clean and deadlift

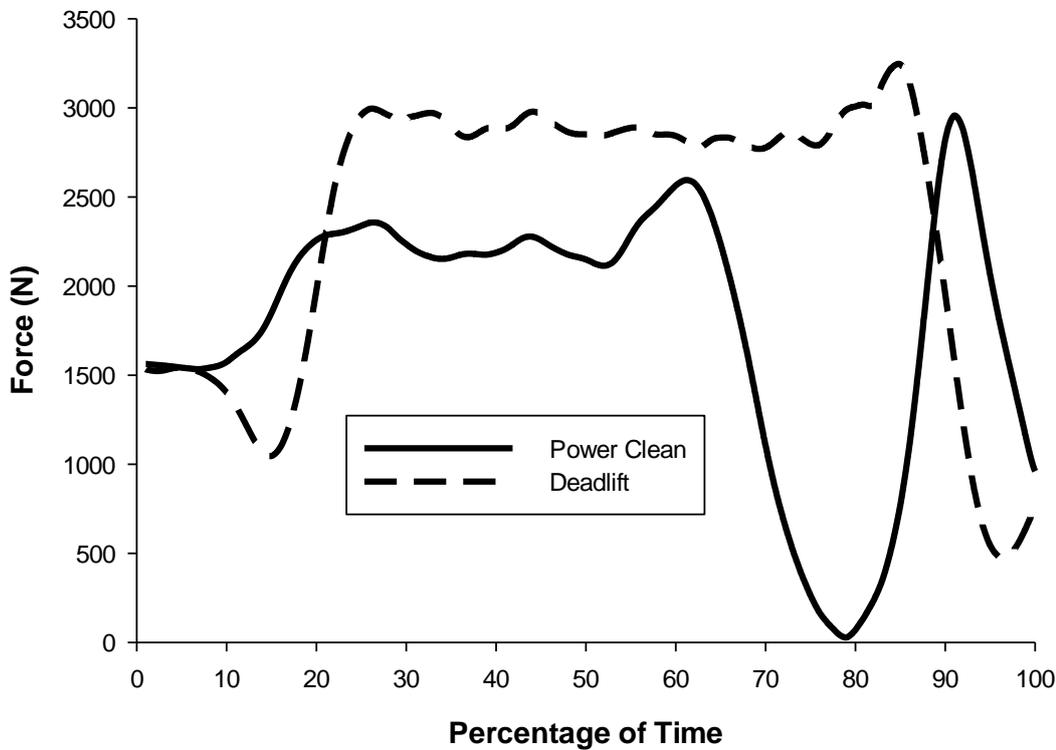
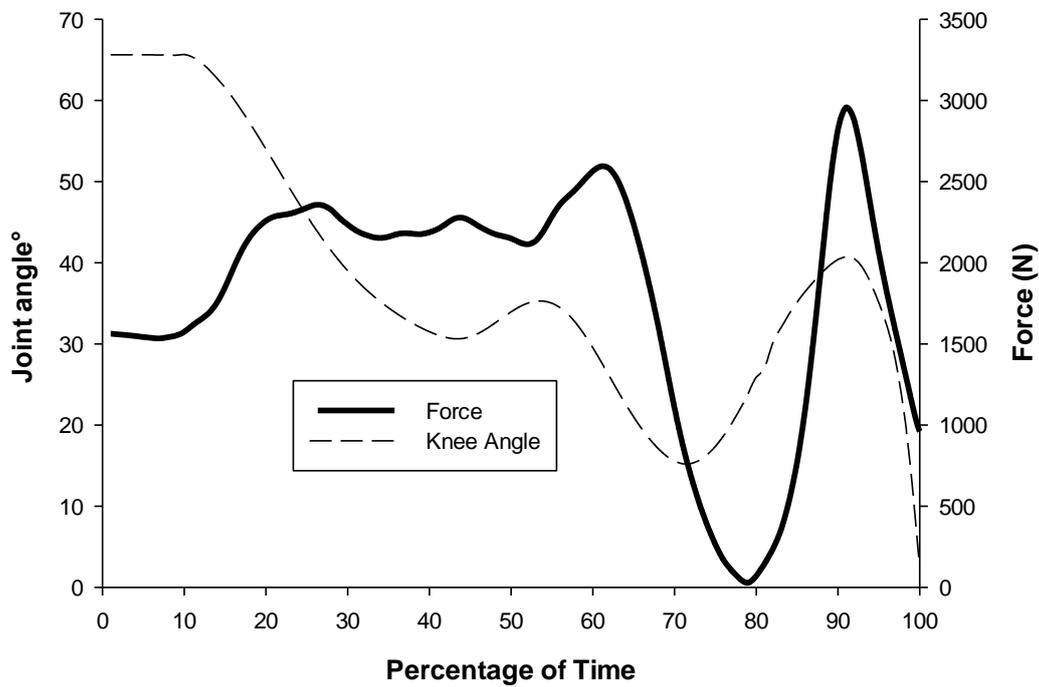
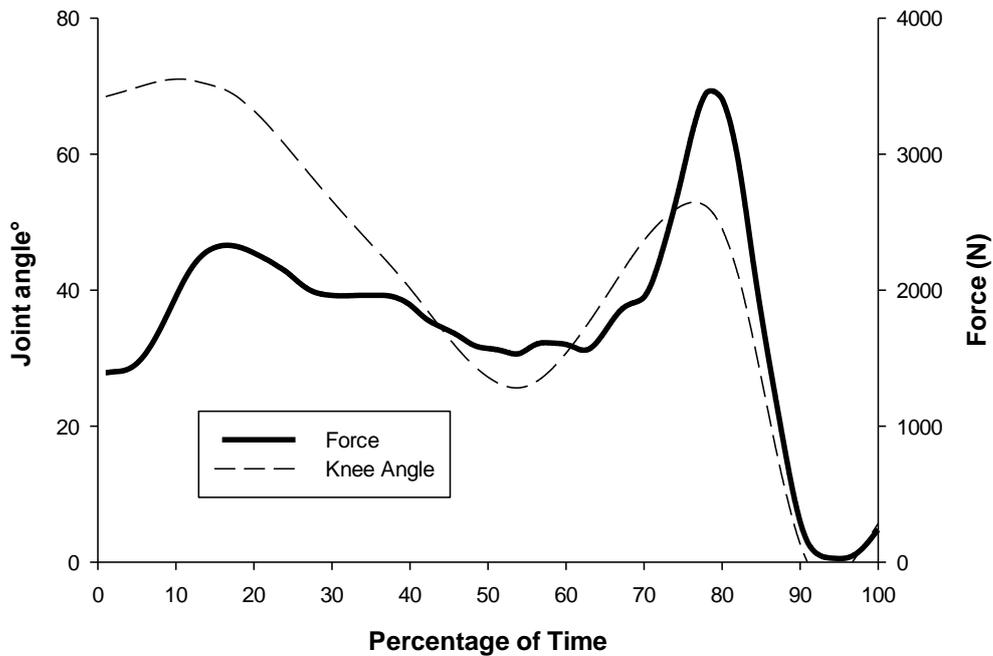


Figure 6.3 illustrates the close relationship between the force-time profile and joint angle-time curve of the knee during the middle and latter stages of the power clean. In contrast to the simple progressive extension curve that was measured at the knee during the deadlift, a prominent second phase where the knee flexes and then rapidly returns to extension was observed during the power clean. Interestingly, one of the participants utilised a similar extension-flexion-extension knee joint pattern when performing repetitions in the deadlift (Figure 6.4). For the same individual the force-time curve developed during the deadlift was distinct from the rest of the group and exhibited the same bimodal profile and higher PRFD values measured during power cleans.

**Figure 6.3:** Representative force-time and knee joint-time curves obtained during the power clean



**Figure 6.4:** Distinct force-time and knee-joint time curves obtained during the deadlift (single individual)



The extent of the acceleration phase expressed relative to the repetition duration and barbell displacement revealed significant main effects of exercise type. Across all loads the

extent of the acceleration phase was greatest for the deadlift compared with the power clean (Table 6.4). At the point at which the participants began to decelerate, the velocity of the barbell was measured to calculate the kinetic energy transferred to the external resistance during the acceleration period. The results show that greater velocity created during the power clean transferred more kinetic energy despite the two-fold greater masses lifted during the deadlift.

**Table 6.4:** Acceleration and kinetic energy data for the power clean and deadlift (mean±SD)

|                           | Power Clean |            |            | Maximum deadlift |             |             |
|---------------------------|-------------|------------|------------|------------------|-------------|-------------|
|                           | 40% 1RM     | 60% 1RM    | 80% 1RM    | 40% 1RM          | 60% 1RM     | 80% 1RM     |
| % Time Acceleration       | 59.1 ± 3.2  | 60.1 ± 3.0 | 68.3 ± 4.1 | 73.9 ± 4.1*      | 80.4 ± 3.8* | 78.2 ± 5.4* |
| % Bar Travel Acceleration | 62.2 ± 3.0  | 65.6 ± 3.6 | 69.2 ± 3.9 | 75.5 ± 5.3*      | 83.8 ± 6.1* | 79.9 ± 5.4* |
| Kinetic Energy (J)        | 159 ± 32*   | 172 ± 51*  | 166 ± 24*  | 121 ± 28         | 91 ± 18     | 29 ± 8      |

\*Significantly greater than corresponding condition (p<0.05).

Comparisons of the internal kinematics and kinetics revealed significant main effects for sagittal joint angles, with greater amounts of flexion obtained at the hip, knee and ankle at the start of the concentric phase of the power clean (Table 6.5). For each segment, significant interaction effects of load and exercise were obtained for peak joint velocities. The results revealed that joint velocities remained relatively consistent across loads in the power clean, whereas, peak values dropped considerably between 60% and 80% 1RM loads in the deadlift. Despite the large differences in velocity measured at the barbell, joint angular velocities were similar for the deadlift and power clean during the two lightest conditions (Table 6.5). Significant main effects of load and exercise were also obtained for peak joint moments at each segment. Greater values were obtained during the deadlift for the hip, ankle and torso, with the power clean producing greater peak joint moments at the knee. The divergent patterns of joint moments and velocities across the loads resulted in a more complex outcome for joint powers (Table 6.6). At the knee joint greater peak joint power was produced during the power clean across all loads. Whereas, for other joints, power values were similar for both exercises during the lighter load conditions and generally were greater during the power clean at the heaviest load.

**Table 6.5:** Sagittal plane angles for the power clean and deadlift at the start of movement (mean±SD)

|                 | Power Clean  |              |              | Maximum deadlift |             |             |
|-----------------|--------------|--------------|--------------|------------------|-------------|-------------|
|                 | 40% 1RM      | 60% 1RM      | 80% 1RM      | 40% 1RM          | 60% 1RM     | 80% 1RM     |
| Torso flex/ext° | 50.3 ± 10.1  | 50.4 ± 12.5  | 51.0 ± 14.4  | 55.8 ± 10.0*     | 56.2 ± 11.2 | 59.6 ± 13.3 |
| Hip flex/ext°   | 102.0 ± 5.8* | 103.2 ± 6.5* | 103.0 ± 8.4* | 90.3 ± 7.1       | 89.6 ± 7.0  | 92.7 ± 7.0  |
| Knee flex/ext°  | 86.4 ± 8.2*  | 85.3 ± 9.7*  | 80.7 ± 10.2* | 71.7 ± 10.2      | 70.6 ± 9.4  | 70.5 ± 9.6  |
| Ankle flex/ext° | 29.6 ± 3.7*  | 30.5 ± 3.9*  | 29.0 ± 4.1*  | 22.3 ± 3.8       | 21.7 ± 4.7  | 23.2 ± 4.6  |

\*Significantly greater than corresponding condition (p<0.05).

**Table 6.6:** Peak joint- velocity, moment and power data for the power clean and deadlift (mean±SD)

|               | Power Clean |           |            | Maximum deadlift |            |           |
|---------------|-------------|-----------|------------|------------------|------------|-----------|
|               | 40% 1RM     | 60% 1RM   | 80% 1RM    | 40% 1RM          | 60% 1RM    | 80% 1RM   |
| <b>Torso</b>  |             |           |            |                  |            |           |
| Peak Velocity | 233 ± 56    | 227 ± 33  | 200 ± 36   | 231 ± 64         | 194 ± 43   | 100 ± 23  |
| Peak Moment   | 294 ± 53    | 300 ± 46  | 310 ± 42   | 334 ± 42*        | 386 ± 51*  | 410.± 61* |
| Peak Power    | 368 ± 134   | 355 ± 165 | 388 ± 120  | 279 ± 85         | 320 ± 104  | 240 ± 83  |
| <b>Hip</b>    |             |           |            |                  |            |           |
| Peak Velocity | 314 ± 68    | 289 ± 64  | 267 ± 62*  | 310 ± 65         | 250 ± 75   | 124 ± 27  |
| Peak Moment   | 210 ± 22    | 223 ± 26  | 240 ± 29   | 251 ± 26*        | 299 ± 31*  | 325 ± 38* |
| Peak Power    | 693 ± 215   | 750 ± 239 | 685 ± 174  | 748 ± 194        | 780 ± 153  | 440 ± 121 |
| <b>Knee</b>   |             |           |            |                  |            |           |
| Peak Velocity | 217 ± 52    | 240 ± 57  | 237 ± 63   | 267 ± 58         | 230 ± 72   | 104 ± 43* |
| Peak Moment   | 118 ± 56*   | 122 ± 38* | 154 ± 44*  | 72 ± 22          | 88 ± 25    | 90 ± 28   |
| Peak Power    | 241 ± 128   | 264 ± 89  | 301 ± 190* | 150 ± 116        | 155 ± 92   | 87 ± 24   |
| <b>Ankle</b>  |             |           |            |                  |            |           |
| Peak Velocity | 172 ± 88    | 230 ± 89  | 250 ± 78   | 294 ± 68*        | 306 ± 70*  | 120 ± 67  |
| Peak Moment   | 141 ± 29    | 164 ± 29  | 186 ± 33   | 175 ± 21*        | 208 ± 29*  | 216 ± 22* |
| Peak Power    | 217 ± 76    | 369 ± 140 | 501 ± 190* | 512 ± 184*       | 500 ± 160* | 164 ± 89  |

Peak velocity ( $^{\circ}\text{s}^{-1}$ ), Peak Moment (Nm), Peak Power (W). \*Significantly greater than corresponding condition (p<0.05).

## 6.5 Discussion

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The present study investigated the biomechanical effects when progressing from sub-maximum to maximum velocity repetitions in a traditional resistance exercise such as the deadlift. In addition, the biomechanical stimulus created during maximum velocity repetitions was compared with that produced during the power clean. The results of the study revealed that the increased velocity obtained when attempting to lift the load as fast as possible enhanced a range of kinematic and kinetic variables. The comparison of the stimulus created between the deadlift and power clean demonstrated that in addition to the expected differences there were a number of interesting similarities which have previously not been discussed in the literature. Collectively, the results from this study provide support for the practice of performing ERT with an exercise such as the deadlift and thereby contradict recommendations made by the majority of researchers in the field of strength and conditioning.

Recent studies investigating the effects of repetition velocity during performance of free-weight exercises have focused on comparisons of sub-maximum velocities categorised as fast, moderate and intentionally slow (Hatfield et al. 2006, Lachance and Hortobagyi 1994, Sakamoto and Sinclair 2006). Results of these comparisons have demonstrated that fast repetitions produce greater values for force, power, RFD, muscle recruitment and overall training volume (Hatfield et al. 2006, Lachance and Hortobagyi 1994, Sakamoto and Sinclair 2006). In previous studies fast repetitions were defined as cadences of one second or less, with moderate velocities extending from one to two seconds (American College of Sports Medicine 2009, Morrisey et al. 1998). According to these categorisations, the athletes in the present study performed all sub-maximum velocities in the deadlift at moderate speeds. Despite individuals self selecting the velocity used to perform each repetition, variation across the group was small with the duration of lifts increasing disproportionately with heavier loads. A similar progression was obtained for maximum velocity deadlifts. These results suggest that the athletes regulated their performance during the sub-maximum trials not by attempting to adhere to a set cadence, but by exerting a relative percentage of their maximum capability. Based on this assumption, it is not surprising that increased effort applied during maximum velocity repetitions resulted in greater values for force, RFD, joint moments and joint powers. However, results that would have been difficult to predict a priori include different joint orientations adopted at the start of the movements and alterations to the vertical displacement of the barbell. Greater hip and

knee flexion angles measured during lighter load conditions with sub-maximum velocity deadlifts may reflect the reduced effort and the selection of a body posture which is frequently advocated but less effective from a mechanical perspective (Hales 2010). In contrast, the more extended hip and knee angles used during maximum velocity lifts would enable greater forces to be produced through enhanced muscle length-force characteristics and reduced resistance moment arms (Hales, Johnson and Johnson 2009, Hales 2010), thereby creating the highest repetitions speeds possible. This hypothesis also explains why participants adopted the same joint angles during the heaviest load condition where considerable effort must be exerted even when attempting to complete the lift at sub-maximum velocity.

The increased barbell elevation measured during maximum velocity deadlifts reflects the different constraints of each condition. To avoid projecting the body into the air the greater velocity created during maximum effort repetitions must be actively decelerated or partly transformed into increased mechanical energy of the external resistance. Analysis of joint angle-time curves of the ankle reveal that there was significantly greater plantar flexion at the end of maximum velocity repetitions and that the amount of plantar flexion decreased as the load became heavier. By rapidly plantar flexing the ankle at the end of the deadlift, power can be transferred from the knee to the ankle through the action of the biarticular gastrocnemius, contributing to an overall deceleration at the knee (van Ingen Schenau 1989). The conditions that produced the greatest velocities resulted in the largest plantar flexion angle which at least partly explains the increased elevation of the barbell. It is also possible that additional vertical elevation was achieved by allowing the shoulder girdle to rise or the elbows to flex. Additional research conducted from this PhD project demonstrated that the act of plantar flexing the ankles at the terminal stage of the deadlift significantly increased force, velocity and power compared to repetitions that were terminated with the heel on the ground (Swinton, Agouris, et al. 2010a). From the same work it was suggested that plantar flexion provides a longer period for force production and acceleration which could explain the increase in mechanical variables measured.

Researchers that have recommended against performing traditional resistance exercises explosively have done so based primarily on the belief that the exercises require extensive periods of deceleration and reduced force production to slow velocity to zero at the end of the movement (Kraemer and Fleck 2004, Newton and Kraemer 1994). The first investigation to analyse force and acceleration profiles throughout the duration of a

traditional resistance exercise was conducted by Lander et al. (1985). Their results showed that when a load of 75% 1RM was lifted explosively in the bench press, approximately one quarter ( $26.5 \pm 4.7\%$ ) of the exercise duration was spent decelerating the load. A similar experiment using a slightly heavier resistance of 81% 1RM was completed by Elliot et al. (1989). The deceleration period reported was considerably greater than that found in the previous study (Lander et al. 1985), and was shown to be even longer in duration than the acceleration period (51.7% vs. 48.3% respectively). Elliot et al. (1989) suggested that dissimilar results between the two studies may have been due to order effects from the different experimental protocols. A third study conducted by Newton et al. (1997) also incorporated the bench press with a much lighter load of 45% 1RM. The investigators gave participants clear instructions to lift the load as fast as possible and reported that the acceleration phase comprised approximately 60% of the movement duration. It is unclear why such large variation exists across the different studies and may be due to factors such as the experimental population, the data collection protocols and the analysis procedures used. It is possible that individuals with more experience in performing the movement explosively develop strategies that enable them to accelerate the load for longer periods. In addition, each of the previous studies measured acceleration from the second derivative of the barbells position data. This method does not take into consideration acceleration of the system as a whole and is prone to errors that must be smoothed using data filtering procedures (Kipp, Harris and Sabick 2012). Differences in filtering techniques and errors within the measurement system may also have contributed to the variation in results.

In the present study acceleration of the system mass which comprised the participant's body and the external resistance was calculated directly using the VGRF data. The results show that even with loads as light as 40% 1RM, approximately three quarters of the movement can be spent accelerating the load. As the external resistance increased, the percentage of the movement comprising positive acceleration increased to approximately 85%, with some participants accelerating the load for almost 90% of the movement. The different results obtained between the present study and those reported previously may be influenced by the exercises selected. The bench press is a relatively simple exercise that involves only a small number of joints and therefore provides limited movement strategies to decelerate or transfer mechanical energy to the external resistance. In contrast, the deadlift includes coordinated movement across a greater number of segments which enables more complex control strategies to be implemented. The finding that a traditional resistance exercise such as the deadlift can be used to produce acceleration for the majority of the

movement runs contrary to recommendations made by many strength and conditioning researchers.

In addition to concerns regarding the acceleration profile of the movements, many researchers have proposed that traditional resistance exercises should not be used with ERT as they produce substantially less power than ballistic or weightlifting exercises (Stone et al. 2006). The first study to compare the power produced during traditional resistance and weightlifting exercises was conducted by Garhammer and McLaughlin (1980). The authors reported that average power produced during the snatch was approximately double that produced during the squat. Further research from the same primary author concluded that similar differences in average power production existed between the deadlift and clean (Garhammer 1993). It was concluded that lower power produced during the squat and deadlift was attributable to relatively slow vertical velocities generated throughout the movement (Garhammer 1993). However, the studies were carried out during powerlifting and weightlifting competitions where participants were lifting maximum loads. From previous studies it is known that the largest power values are produced with sub-maximum loads for traditional resistance exercises ( $\approx$  30 to 60% 1RM), whereas maximum power is produced with loads close to 100% 1RM during weightlifting movements (Cormie, McGuigan and Newton 2011). To more appropriately investigate power production and related variables the present study included an extensive biomechanical analysis over a range of loads. The power clean was selected rather than the squat clean as this particular variant is less technically demanding and has been shown to create similar kinematic and kinetic profiles to the full movement (Souza, Shimada and Koontz 2002). Results from the present study confirm that greater average and peak external power is produced during a weightlifting movement compared to a traditional resistance exercise. However, the magnitude of the difference is considerably less than that reported by Garhammer (1993). The results show that maximum power values were approximately 20% greater during the power clean compared with deadlift (4.9 kW vs. 4.1 kW). As both exercises were initiated with the barbell positioned stationary on the floor a forward dynamics approach to calculate external power was not suitable. Instead, external power was calculated as the product of the vertical GRF and vertical velocity of the barbell. There are limitations with this method as it assumes that velocity of the barbell is representative of the systems velocity. Recent research has suggested that this assumption may be erroneous with most resistance exercises and consistently lead to overestimations of power (Lake, Lauder and Smith 2012). Therefore, whilst the data provide some insight into the external power produced and make

available numerical values which can be compared to previous studies, interpretation of the results must be made with caution.

To compare the biomechanical stimulus of the deadlift and power clean it is important not only to consider external power, but also the force profile, joint angular velocities, joint moments and internal joint powers. The power clean has been shown previously to produce force-time curves that are distinct from non-weightlifting exercises (Souza, Shimada and Koontz 2002); in particular, the movement creates a distinctive bimodal pattern. The entire force-time curve comprises three major sections which correspond to the first pull, the unweighting phase and the second pull (Souza, Shimada and Koontz 2002). Each of the athletes in the present study reproduced these distinct phases. The second pull is considered to be the most important feature of the power clean as it is this phase where peak values of kinetic variables are produced and the motion is thought to be similar to many important sporting actions (Stone et al. 2006). Comparisons of the force-time profiles of the deadlift and power clean confirmed that VGRF values were generally greater during the deadlift, but only the power clean included a distinct bimodal pattern. Analysis of the time derivative of the force-time curves revealed that the unweighting and subsequent second pull phases of the power clean enabled production of substantially higher RFD values than those produced during the deadlift. As found here and in previous studies (Souza and Shimada 2002), a clear connection exists between the joint-angle profile of the knee and the force-time characteristics expressed during the unweighting and second pull phases. In the literature the motion of the knee during these phases is referred to as the double-knee bend (Stone et al. 2006). The movement is presumed to augment kinetic variables through a SSC action which may exploit a combination of mechanisms including the use of stored elastic energy, the myotatic reflex, optimisation of muscle length relationships and enhancement of muscle activation patterns (Stone et al. 2006). In the present study, one of the participants utilised the same double-knee bend technique during the deadlift which resulted in a force profile similar to that observed for the power clean. Interestingly, the participant who adopted this technique was the only individual who produced similar peak RFD values for both the power clean and deadlift. It is therefore possible that the inclusion of the double-knee bend technique during explosive deadlifts could provide a better stimulus than conventional techniques to enhance RFD. In addition, incorporation of the double-knee bend technique during the deadlift could potentially serve as an appropriate progression when teaching the power clean to athletes. Future research is required to determine whether the data obtained here from the single participant can be replicated in a larger sample.

Despite the substantially greater barbell velocities obtained during the power clean, the joint angular velocities revealed that the highest values obtained across the loads were similar for both exercises. In general, angular velocities obtained during the power clean only diminished slightly as the external resistance was increased. One notable exception to this trend was observed at the ankle joint, where peak angular velocity increased with heavier loads. In contrast, substantial decreases in joint angular velocities were obtained with the deadlift as the load increased from 60 to 80% 1RM. This finding reinforces why previous investigations of the deadlift during competitions fail to produce data representative of the biomechanical stimulus created when using lighter resistances.

The heavier absolute loads lifted in the deadlift compared with the power clean resulted in significantly greater joint moments at the lumbar spine, hip and ankle. Conversely, significantly greater peak knee moments were obtained during the power clean. Divergent results obtained at the knee joint were likely caused by differences in moment arms that exceeded the effect of the resistance magnitude. During the deadlift the bar was kept close to the shin and thigh ensuring that the moment arm at the knee was small. In contrast, increased knee angles at the start of the power clean and during the second pull created much larger resistance moment arms, which would have increased the overall resistance and thereby explain the larger net joint moments produced. The use of inverse dynamics to calculate net joint moments and angular velocities provides the opportunity to calculate joint powers. Where external power provides information at the barbell or lifter-barbell system, joint power provides information of the rate of mechanical work applied to specific segments of the body (Zatsiorsky 2002). This information may be useful in the design of resistance training programs to enhance performance in specific sporting movements (Kipp, Harris and Sabick 2012). Only a few studies have provided internal power values during resistance training exercises (Enoka 1988, Kipp, Harris and Sabick 2012). This may be due to the expensive equipment and labour intensive data collection and processing procedures required. Studies that have been conducted have shown that joint power is affected by load magnitude in a similar manner to that observed with external power (Kipp, Harris and Sabick 2012). However, research comparing internal and external power values has shown that the two variables do not necessarily correlate with one another, particularly for lighter resistances where values appear to diverge (Kipp, Harris and Sabick 2012). For the power clean maximum peak values generally occurred at 60 or 80% 1RM loads, whereas maximum peak joint power values for the deadlift were obtained at 40 or 60% 1RM. In addition, there tended to be a large drop off in peak power values with the deadlift at the 80% 1RM loads. Despite differences obtained in the pattern of values across the loads,

similar maximum values were produced for the deadlift and power clean. The one exception was at the knee joint where peak power values were significantly greater during the power clean in comparison to the deadlift. These results illustrate the limitations of relying solely on external power to provide information on the rate at which energy is applied to the different segments of the body. In addition, the results provide further evidence that recommendations made by researchers to avoid performing traditional resistance exercises with ERT are unwarranted. Further research should be conducted to investigate the temporal characteristics of joint power values to determine if the information can be used to enhance the mechanical specificity and transfer of training to sporting actions.

Comparisons of the length and duration of the acceleration phase during the deadlift and power clean revealed that the magnitude was significantly greater during the deadlift. It has been acknowledged that weightlifting exercises such as the power clean can include a relatively extensive period of deceleration; however, the exercises are still recommended by researchers as it is suggested that there is minimal active deceleration and instead energy is transferred to the barbell and subsequently slowed by the effects of gravity (Cormie, McGuigan and Newton 2011). To investigate this proposed mechanism and determine the extent to which the same process may be adopted in the deadlift, the kinetic energy of the barbell was calculated at the point at which the overall system began to decelerate. The results showed that more kinetic energy was transferred to the barbell during the power clean as a result of the greater velocities created (Table 6.4). However, the results also demonstrated that during the lighter load conditions substantial amounts of kinetic energy were transferred to the barbell during the deadlift, with some athletes exhibiting more proficiency than others.

## 6.6 Summary and Conclusion

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The current study demonstrates that performing an exercise such as the deadlift with the intent to lift the load as fast as possible significantly increases values obtained for many key mechanical variables in comparison to the standard practice of lifting loads with sub-maximum velocity (and hence sub-maximum effort). These results provide strong support for one of the primary training practices promoted by contemporary powerlifters.

To investigate whether the practice may be beneficial for general athletes the biomechanical stimulus created with the deadlift was compared with the power clean, which is one of the most popular exercises prescribed to athletes. The results highlighted that the stimulus developed with the two exercises are more closely related than researchers would previously have considered. In general, greater velocities were obtained during the power clean, especially with heavier relative loads. However, similar maximum peak joint velocities and peak joint powers were produced with both exercises. Additionally, the heavier absolute loads lifted with the deadlift resulted in greater net joint moments. Collectively the results suggest that the deadlift would be an appropriate exercise for athletes when attempting to develop muscular power or general athleticism. It is important to note that these findings characterise only the basic approach used by powerlifters to develop their explosive performance. As highlighted in chapter three, the majority of powerlifters seek to enhance maximum velocity lifts through the addition of variable resistance material such as bands and chains, and through the use of unconventional barbells and altered movement strategies. These complimentary training practices will be investigated in chapters seven and eight.

## CHAPTER 7. MANIPULATION OF THE EXTERNAL RESISTANCE

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### 7.1 Prelude

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As highlighted in chapter three, one of the central features of powerlifters' contemporary training practices includes the manipulation of the external resistance. Two of the most popular and visually recognisable methods are the inclusion of variable resistance material in the form of bands and chains, and the use of unconventional barbells. Both methods are used primarily as strategies to augment the biomechanical stimulus created when performing traditional resistance exercises explosively. In particular, the addition of bands and chains are believed to extend the duration of high level force output during the propulsive phase of the movement. In contrast, unconventional barbells are used to alter the distribution of mechanical stress created by the external resistance. This latter process is believed to have the potential to enhance the overall stimulus and enable athletes to target specific segments of the body. As the use of chains and bands has become synonymous with the contemporary training practices of powerlifters, a substantial research base has been created over a relatively short time period. However, the specific loading characteristics that have been investigated thus far do not adhere to those commonly used by high-level powerlifters. Conversely, the use of unconventional barbells has received almost no academic consideration. Therefore, the purpose of this chapter is to compare the biomechanical effects of variable resistance materials and unconventional barbells with suitable controls. The experiments were also designed to determine if the practices could be used to augment the stimulus created when performing traditional resistance exercises explosively.

## 7.2 Introduction

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Simple models which are used to conceptualise the potential stimulus from a bout of resistance training may feature the exercise, the magnitude of the resistance and the number of repetitions performed as the primary variables. Using such a model, it may be assumed that loading of tissues is primarily influenced by the magnitude of the resistance and the specific exercise selected. As found in chapter three of this thesis, many powerlifters view their performance in a specific exercise as being limited by the weakest link in the kinematic chain or region with the lowest force capability. As a result, powerlifters frequently select combinations of loads and exercises to target specific segments of the body and/or regions of the movement believed to limit performance. However, just as the transfer of resistance training to sports performance is dependent upon a number of principles of specificity, so too is the transfer of adaptations between different exercises (Bondarchuk 2007). To increase the likelihood of adaptations improving performance, powerlifters often perform the specific exercise but restrict the range of motion to focus on the region of the movement where performance is at its lowest (Simmons 2007). This section of the movement has been termed the sticking region and corresponds to the location where the vector sum of the resistive and propulsive torques is at its minimum (McGuigan and Wilson 1996). This training practice generally requires athletes to select sub-maximum resistances and perform short amplitude movements above and below the sticking region (Siff 2003). Taking the method to its limit, powerlifters may position the load at the sticking region and perform maximum isometric actions (Siff 2003). This strategy is supported by research which has demonstrated that isometric training generally produces the largest improvements in maximum force at or near the joint angles used in training (Kitai and Sale 1989, Weir et al. 1995).

A significant break-through in the training methods of powerlifters was made when resistance was conceptualised as more than a given number of kilograms (i.e. a magnitude). Through understanding that resistance could be considered as a composite of factors including the type of resistance material and its location relative to joint centres, novel training practices have emerged. The majority of powerlifters now regularly alter the composition of resistance material through the inclusion of bands and chains. The total resistance then varies throughout an exercise depending on the distance of the barbell from a datum and the subsequent stretch of elastic material or mass of chains unfurled from the

floor. Generally, full repetitions are performed and the variation in resistance can be used to provide appropriate overload at specific regions of the movement. In contrast, understanding the importance of the load's position relative to joint centres enables more emphasis to be placed on targeting the weakest link in the kinematic chain rather than specific regions of the movement. This training effect can be achieved by simply translating the position of the barbell during a given exercise. A common example includes the high-bar vs. low-bar positioning in the squat which has been shown to influence the distribution of mechanical stress at the hip and knee (Wretenberg, Feng and Arborelius 1996). However, the amount of translation that can be achieved with a conventional barbell is generally limited to a short distance. Instead, powerlifters have developed a range of unconventional barbells which enable greater translation of the external resistance. The most popular unconventional barbells include the hexagonal-, cambered- and safety squat-barbell (Figure 7.1).



**Figure 7.1:** The hexagonal- (left), cambered- (middle) and safety squat-barbell (right)

Of the two methods commonly used by powerlifters to manipulate the external resistance, the inclusion of bands and chains has received more considerably attention from researchers. Biomechanical investigations have assessed whether the inclusion of variable resistance material can enhance the stimulus of explosive repetitions. In an early study conducted by Cronin et al. (2003) the effects of rubber bands on EMG activity and movement velocity were investigated. The testing movements included the traditional squat, jump squat and augmented jump squat with the inclusion of rubber bands. A single familiarisation session was provided but no additional information was given regarding the participants proficiency with any of the testing movements. The results showed that peak velocity and EMG activity of the vastus lateralis were greater during the jump squat

conditions compared with the traditional squat ( $1.0 \text{ ms}^{-1}$  vs.  $0.6 \text{ ms}^{-1}$  and 63.5% vs. 29.2%, respectively). However, no additional effects were obtained when rubber bands were included. Unfortunately the authors did not include an additional condition to assess whether the stimulus of the traditional squat could be improved by adding the variable resistance material. This comparison was investigated in a study conducted by Ebben and Jensen (2002). The participant population comprised a heterogeneous group of male and female athletes with large variation in maximum strength capabilities. The authors found no significant differences in peak force or EMG activity (quadriceps and hamstrings) between squats performed with or without rubber bands. The authors did report that participants noted qualitatively, squatting with rubber bands “felt” different. The results of the study should be interpreted with caution as limited information was provided regarding the participants’ experience with variable resistance material and the rubber bands accounted for only 10% of the overall load which is unlikely to create differences in such a heterogeneous group. In a study conducted by Wallace et al. (2006) the effects of attaching very stiff rubber bands to the traditional squat was investigated. Participants performed the experimental and control repetitions with a total resistance equal to 65 and 80% 1RM. For the experimental condition 20 and 35% of the overall resistance was replaced with the rubber bands. The results showed that variable resistance material could be used to produce significantly greater peak force and power values compared with the control condition. Interaction effects also revealed that the magnitude of improvements depended on the combination of the overall resistance and percentage contribution from rubber bands. The greatest increases were obtained when using the heaviest overall load, with participants’ peak force increasing by 5 and 16% when rubber bands accounted for 20 and 35% of the total resistance, respectively. The greatest increases in peak power were also obtained with the heaviest overall load; however, optimal results were obtained when rubber bands accounted for only 20% of the overall resistance (24% vs. 8% improvement). The authors hypothesised that increases in mechanical variables were due to provision of greater resistance at the positions where the length-tension relationship of muscles were at their optimum (Wallace and Winchester 2006).

Fewer studies have investigated the biomechanical stimulus created when the variation to resistance has been achieved by the inclusion of chains. In contrast to the relative ease with which rubber bands can be stored and attached to the barbell, heavy chains provide more of a logistic challenge. However, the contribution to the resistance may be more precisely calculated when using chains as compared with resistance created from rubber bands which will be influenced by a material’s viscoelastic properties (McMaster, Cronin and

McGuigan 2009). The first study to investigate the use of chain resistance was conducted by Ebben and Jensen (2002). The authors reported that the inclusion of chains had no effect on kinetics or EMG activity during the back squat. Coker and colleagues also failed to report any effects on the kinematics and kinetics of the snatch (Coker, Berning and Briggs 2006) and clean (Berning, Coker and Briggs 2008). In contrast, Baker and Newton (2009) reported that the inclusion of chains significantly increased mean and peak lifting velocities during the bench press. Conflicting results between studies may be explained by the different magnitudes of chain resistance used. In each of the previous studies repetitions performed with a constant barbell load were compared with repetitions where a portion of the mass was substituted with chains. Studies reporting no significant differences substituted 6 to 10% of the barbell mass with chains (Ebben and Jensen 2002, Berning, Coker and Briggs 2008, Coker, Berning and Briggs 2006), whereas, Baker and Newton (2009) obtained significant increases in lifting velocity when substituting on average 25% of the barbell mass. The contrasting results suggest that a minimum amount of chain mass may be required to alter exercise kinematics and kinetics. Based on their own findings and results from similar studies investigating the use of rubber bands, Baker and Newton (2009) recommended that chain masses greater than 15% of a lifter's maximum strength should be used when attempting to alter the mechanical stimulus of an exercise. However, information from lay sources (Simmons 2007) and interviews conducted in chapter three of the current project reveal that powerlifters routinely use chain and band resistances which account for up to 60% of their 1RM. It is important, therefore, that research is conducted which includes loading characteristics representative of that used by the athletes that consistently use the practice.

Each of the biomechanical studies that have investigated the use of bands and chains has ensured that all repetitions were performed explosively. This design corresponds with the primary use of variable resistance material which is to enhance the stimulus of ERT, particularly when using traditional resistance exercises. Interestingly, only one study thus far has investigated the central hypothesis that increasing resistance from stretched bands or unfurled chains enables maintenance of high force production until the end of the movement. Israetel et al. (2010) recruited ten recreationally weight trained males to perform the back squat with and without rubber bands. Force data was sampled at 1000Hz and collected across the eccentric and concentric phases of the motion. An average force-time curve was obtained for the group by resampling individual data on a normalised time scale. In support of the hypothesis, the results showed that significantly greater force was obtained during the final 10% of the concentric movement when using rubber bands. Despite

equating the average load lifted in each condition, the authors set the resistance in the experimental condition to comprise almost entirely resistance from rubber bands (the only inertial load was that of the barbell). This type of loading is not representative of the practices used and promoted by powerlifters and therefore further research is required to test the central hypothesis of variable resistance material.

An additional important aspect of variable resistance material that has not been investigated in sufficient depth is the interaction effect of the overall resistance and the percentage comprised from either bands or chains. Only two studies that have investigated the effects of chain resistance have used more than one barbell load in their experimental protocol (Berning, Coker and Briggs 2008, Coker, Berning and Briggs 2006). In addition, both studies included loads that differed by only 5% 1RM (75 vs. 80% 1RM). A similar lack of multiple loading conditions has featured in studies investigating the use of rubber bands. One notable exception includes the work conducted by Wallace et al. (2006). As previously discussed, the authors included total resistances of 65 and 80% 1RM and featured two different rubber band conditions comprising 20 and 35% of the total resistance. The interaction effects reported provide some initial insight into possible relationships between the total and variable resistance. However, to effectively prescribe variable resistance material further study of the interaction between inertial and variable loads is required.

In contrast to the relatively large number of studies that have investigated the biomechanical stimulus of variable resistance material, to the author's knowledge there has only been one study published that has investigated the use of an unconventional barbell. The study was conducted by Lander et al. (1986) and compared joint kinetics of six experienced male weightlifters performing the squat with a regular barbell and a cambered barbell (Figure 7.1). The unconventional barbell had an adjustable frame that could be used to alter the vertical distance of the weightlifting plates relative to the crossbar. The authors proposed that the unconventional barbell could be used to reduce the stress on the lumbar area by reducing the muscular effort required to stabilise the torso in the mediolateral direction (Lander, Bates and Devita 1986). The participants performed three different conditions with the same 5RM load. During the first condition the barbell COM was set at shoulder height, whereas during the second and third conditions the barbell COM was lowered by 18 and 36% of the participant's height. No significant differences were obtained for kinetics analysed at the spine, hip, knee or ankle. However, the authors suggested that

reduced IAP values measured with the unconventional barbell indicated lower compression forces experienced at the lumbar spine.

Another unconventional barbell which is also believed to reduce the mechanical stress experienced at the lumbar spine is the hexagonal barbell. This apparatus is frequently used when performing the deadlift and is the most popular unconventional barbell used by powerlifters and general athletes (Shepard 2009). To minimise the likelihood of sustaining an injury during regular deadlifts athletes are instructed to position the barbell close to the body throughout the movement to reduce the torque of the resistance (Graham 2000). With a conventional barbell the moment arm of the external resistance can be reduced only up to the point where the barbell impinges on the body. The hexagonal barbell was created in order to overcome this restriction and further reduce the resistive torque on the body. The design of the barbell positions individuals within its frame and arranges the load closer to the hip and torso (Figure 7.1). It is also commonly believed that the hexagonal barbell redistributes mechanical stress created during the deadlift, with reductions at the lumbar spine transferred to joints such as the knee (Shepard 2009). However, there have been no published reports or empirical data supporting this theory of altered distribution of the mechanical load.

This limited information in relation to both variable resistance material and unconventional barbells makes evaluation of current training practices difficult. Consequently, to expand on the work from the previous chapter and assess whether either practice could be used to enhance the stimulus associated with ERT, the deadlift was used as the base exercise. Chains were selected to study variable resistance material as more precise loads could be formed to correspond with a percentage of each participant's 1RM. In addition, the hexagonal barbell was selected to compliment the deadlift and increase generalisability of the results based on the popularity of the exercise.

## 7.3 Methods

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The current investigation was divided into two separate studies (Study 1 and Study 2). Study 1 investigated the effects of including chain resistance when performing explosive repetitions in the deadlift. Study 2 compared the biomechanical stimulus created when performing explosive deadlifts with either a straight or hexagonal barbell.

### **7.3.1 Study 1: Analysis of external kinematics and kinetics of deadlifts performed with and without chain resistance**

#### **Experimental approach to the problem**

A cross-sectional, repeated measures design was used to compare the external kinematics and kinetics of the deadlift performed with and without the inclusion of chain resistance. The investigation was restricted to external kinematics and kinetics as these were the primary variables of interest with this particular training practice. Each participant performed the deadlift with 30, 50 and 70% 1RM loads across three conditions: 1) maximum velocity (MAX); 2) maximum velocity with 20% 1RM chains (MAX20); and, 4) maximum velocity with 40% 1RM chains (MAX40). The MAX condition comprised a constant barbell resistance using standard weightlifting plates. Variable resistance was created for the MAX20 and MAX40 conditions by using a combination of weightlifting plates and chains. Multiple chain and barbell loads were incorporated to investigate potential interaction effects and cover a range of loading parameters commonly used by high-level powerlifters.

#### **Participants**

Twenty three experienced resistance trained athletes (15 powerlifters and 8 rugby union players) volunteered to participate in this study (age:  $26.8 \pm 5.9$  yr; stature:  $180.5 \pm 4.2$  cm; mass:  $107.5 \pm 21.0$  kg; deadlift 1RM:  $227.1 \pm 49.3$ kg; resistance training experience:  $10.7 \pm 4.1$  yr). Each of the athletes regularly performed ERT and had a minimum of one year's resistance training experience using chains. Prior to experimental testing participants were notified about the potential risks involved and gave their written informed consent. Approval

for this study was provided by the ethical review panel at Robert Gordon University, Aberdeen, UK.

## **Study design**

Data were collected for each participant over two sessions separated by one week. The first session was performed in the gymnasium and involved 1RM testing in the deadlift. During the second session participants reported to the laboratory where they performed the deadlift with 30, 50 and 70% 1RM loads across the three conditions (MAX, MAX20 and MAX40). External kinematic and kinetic variables were analysed during the second session only.

### **Session 1 (1RM Testing Procedures)**

Each participant regularly performed 1RM tests and could predict their maximum strength accurately. The 1RM testing protocol used for the deadlift was the same as that outlined in chapter six. Once 1RM testing was complete, participants performed a single deadlift repetition at maximum velocity with 30, 50 and 70% of their heaviest load lifted. Displacement of the barbell was recorded to calculate the sets of chains required for the second testing session.

### **Session 2 (Velocity and Chain Testing Procedures)**

Participants performed their own specific warm-up which generally consisted of 3 to 5 minutes jogging on a treadmill, and then 2 to 4 deadlift sets with a light load (e.g. < 40% 1RM) for 6 to 10 repetitions. Once suitably prepared, participants performed the MAX, MAX20 and MAX40 trials with 30, 50 and 70% 1RM loads in a randomised order. Two metre chains varying in size from 2.54 to 0.64 cm links were attached to the barbell for MAX20 and MAX40 conditions so that the chain mass at the top of the movement was equal to 20 or 40% of the lifters 1RM, respectively. The average resistance lifted in the chain and non-chain conditions were equated by subtracting half the mass of chains at the top of the movement from the initial barbell load. For example, during the MAX20 conditions the barbell load was reduced by 10% of the lifters 1RM so that the total resistance was 10% less than the constant barbell condition at the bottom, equal at the midpoint, and 10% greater at the top. Participants were instructed to hold the barbell stationary at the end of the concentric action to calculate the chain mass raised from the floor. The actual mass of chains lifted by the group was equal to  $21.1 \pm 3.6\%$  1RM and  $38.2 \pm 4.9\%$  1RM. participants

were instructed to keep their elbows straight throughout the deadlift and not to jump with the weight. If these requirements were not met the trial was repeated. Participants were permitted to elevate their heels at the terminal stage of the movement as long as the forefoot remained in contact with the ground. Two repetitions were performed in each trial to facilitate calculation of intra-trial reliability. The repetition that produced the greatest peak velocity was selected for further analysis.

### **Measurement of Kinematic and Kinetic Variables**

Maximum velocity trials were performed with a separate piezoelectric force platform (Kistler, Type 9281B Kistler Instruments, Winterthur, Switzerland) under each foot, in a capture area defined by a seven-camera motion analysis system (Vicon MX, Vicon Motion Systems, Oxford, UK). The centre of the external load was tracked in three-dimensional space by placing retroreflective markers at the ends of the barbell and calculating the position of the midpoint. Marker position and ground reaction force data were captured at 200 and 1200Hz respectively. The area under the VGRF-time curve was integrated using Simpson's Rule (Hildebrand 1974) to calculate impulse. Velocity and acceleration were calculated by taking the first and second derivative of the marker position data using a Lagrangian five point differentiation scheme (Hildebrand 1974). Relative phase of acceleration was calculated by expressing the positive acceleration data of the barbell relative to the duration of the repetition and the total vertical displacement of the barbell. Instantaneous power was calculated as the product of the VGRF and corresponding barbell vertical velocity. The starting point of the concentric action was defined as the point where the centre of the barbell was raised 2 mm vertically above its initial resting position. The end of the concentric action was defined as the point where the centre of the barbell reached maximum vertical elevation.

### **Statistical Analysis**

Intra-trial reliability for each variable analysed was assessed by ICC. As recommended by Baumgartner (2006), ICCs were calculated with a correction factor for number of repetitions performed per trial ( $n = 2$ ) and number of repetitions used in the criterion score ( $n = 1$ ). The corrected ICC values ranged from 0.80 to 0.96. Potential kinematic and kinetic differences were analysed using a 3x3 (condition x load) repeated measures ANOVA. Significant main effects were further analysed with Bonferroni adjusted pair-wise comparisons. Statistical

significance was accepted at  $p < 0.05$ . All statistical procedures were performed using the SPSS software package (SPSS, Version 16.0, SPSS Inc., Chicago, IL).

### **7.3.2 Study 2: A biomechanical comparison of straight and hexagonal barbell deadlifts**

#### **Experimental Approach to the Problem**

A cross-sectional, repeated measures design was used to quantify and compare kinematics and kinetics of the deadlift exercise using two distinct barbells. Internal joint kinematics and kinetics were calculated to investigate whether the choice of barbell had an effect on exercise technique and the internal stresses developed when lifting the same absolute load. External kinematics and kinetics (e.g. vertical GRF, velocity and RFD) were calculated across a range of sub-maximum loads to investigate whether unconventional barbells could be used to enhance the biomechanical stimulus for ERT. Data were collected for each participant over two sessions separated by one week. The first session was performed in the gymnasium and involved 1RM testing in the straight barbell deadlift (SBD) and the hexagonal barbell deadlift (HBD). During the second session participants reported to the laboratory where they performed the SBD and HBD across loads of 10 to 80% of their predetermined SBD 1RM. Kinematics and kinetics were analysed during the second session only.

#### **Participants**

Nineteen male powerlifters participated in the study (age:  $30.2 \pm 5.6$  yr; stature:  $181.5 \pm 4.8$  cm; mass:  $114.5 \pm 22.3$  kg; SBD 1RM:  $244.5 \pm 39.5$  kg; HBD 1RM:  $265.0 \pm 41.8$  kg; resistance training experience:  $13.7 \pm 5.2$  yr). Participants were recruited from the Scottish Powerlifting Association and were active competitors at the time of data collection. Based on the powerlifters most recent competition results the average Wilks score of the group was  $403.6 \pm 39.1$ , thereby characterising the athletes at international standard (Vanderburgh and Batterham 1999, Keogh et al. 2009). The study was conducted three months after a regional competition where the majority of participants were nearing the end of a training cycle aimed at matching or exceeding their previous competition performance. All participants were notified about the potential risks involved and gave their written

informed consent, approved by the ethical review panel at Robert Gordon University, Aberdeen, UK.

### **Session 1 (1RM Testing Procedures)**

Participants were competitive powerlifters who were experienced in performing 1RM tests and could predict their maximum strength accurately. 1RM testing for the SBD and HBD were performed in a randomised order with a 30 minute rest period allocated for recovery between exercises. The specific procedures used for each test were the same as that described in chapter six.

### **Session 2 (Maximum velocity repetitions)**

Participants performed their own specific warm-up which generally consisted of 2 to 4 SBD and HBD sets with a light load (e.g. < 40% 1RM) for 6 to 10 repetitions. Once suitably prepared, participants performed SBD and HBD trials with 10, 20, 30, 40, 50, 60, 70 and 80% of their SBD 1RM in a randomised order. Two repetitions were performed in each trial to facilitate the assessment of intra-trial reliability. Participants were instructed to perform each repetition with maximal effort, attempting to lift the load as fast as possible. A minimum 2 minute rest period was allocated between trials with a longer rest period made available if the participant felt it necessary to produce a maximum performance. Participants were instructed to keep their elbows straight throughout the lift and not to jump with the weight. If these requirements were not met the trial was repeated. Participants were permitted to elevate their heels at the terminal stage of the movement as long as the forefoot remained in contact with the ground. For each trial the repetition that produced the greatest peak velocity was selected for further analysis.

### **Biomechanical Analyses**

The sub-maximum load trials were performed with a separate piezoelectric force platform (Kistler, Type 9281B Kistler Instruments, Winterthur, Switzerland) under each foot, in a capture area defined by a seven-camera motion analysis system (Vicon MX, Vicon Motion Systems, Oxford, UK). Marker position and ground reaction force data were captured at 200 and 1200Hz respectively. Based on a frequency content analysis of the three-dimensional coordinate data, marker trajectories were filtered using a digital fourth-order low-pass

Butterworth filter with a cut-off frequency of 6 Hz. Internal kinematics and kinetics were calculated using the models presented in chapter five. Instantaneous velocities and accelerations were calculated by numerical differentiation of the position data (Hildebrand 1974). Kinematic and kinetic measures for the hip, knee and ankle were calculated for both left and right sides and averaged to obtain single values. The starting point for each trial was defined as the point where the centre of the barbell was raised 2 mm vertically above its initial resting height. The end of each trial was defined as the point where the centre of the barbell reached maximum vertical elevation. Instantaneous power values were calculated as the product of the vertical ground reaction force and corresponding barbell vertical velocity. The moment arm of the resistance was found by calculating the horizontal distance from the geometric centre of the barbell to the joint centres.

### **Statistical Analyses**

Intra-trial reliability was calculated using the same correction factor described in study 1. ICC values for all variables ranged between 0.88 and 0.96. A 2-way repeated measures ANOVA (2 barbell type x 8 load) was used to evaluate potential differences in kinematic and kinetic variables between the exercise variations and across loads. Significant main effects were further analysed with Bonferroni adjusted pair-wise comparisons. Statistical significance was accepted at  $p < 0.05$ . All statistical procedures were performed using the SPSS software package (SPSS, Version 16.0, SPSS Inc., Chicago, IL).

## 7.4 Results

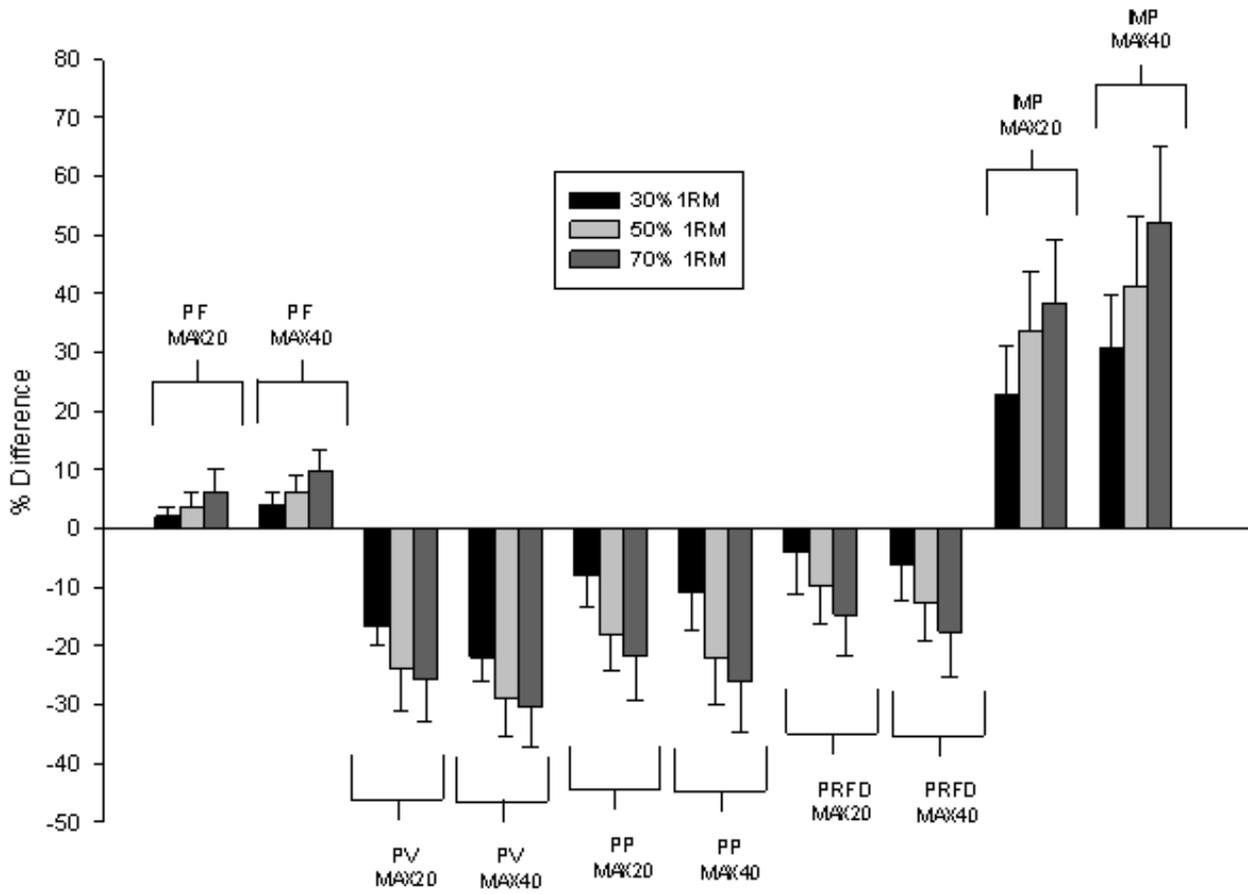
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### **7.4.1 Study 1: Analysis of external kinematics and kinetics of deadlifts performed with and without chain resistance**

Significant interaction effects of load and condition were obtained for average velocity, peak velocity, average power, and impulse ( $p < 0.05$ ). Interaction effects demonstrated that the relative increases and decreases of mechanical variables as a result of including chains became more pronounced as the barbell load increased. The inclusion of chains significantly increased peak force and impulse ( $p < 0.05$ ), and significantly decreased average velocity, peak velocity, average power, peak power, and peak RFD ( $p < 0.05$ ) (Figure 7.2).

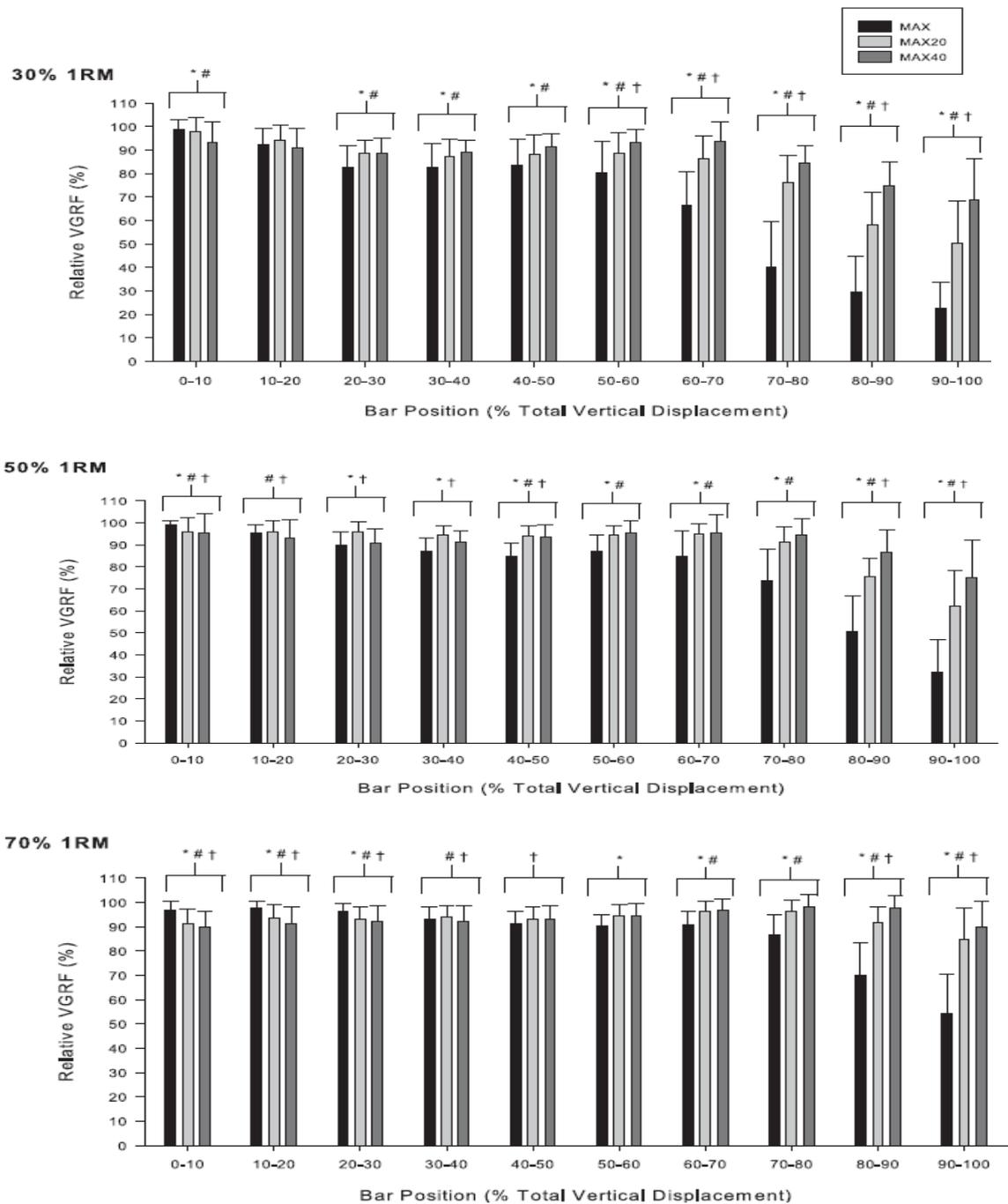
To investigate whether the inclusion of chains enabled high force production to be maintained throughout the concentric action, force values were averaged across 10% intervals of the vertical barbell displacement and normalised relative to the peak value generated during the repetition (Figure 7.3). The results illustrate that inclusion of chain resistance enabled significantly greater relative force to be maintained during the latter portions of the concentric action.

**Figure 7.2:** Kinematic and kinetic data for chain conditions (MAX20, MAX40) with 30, 50 and 70% 1RM loads. Data are expressed as a percentage difference relative to the values obtained for the corresponding non-chain condition (MAX).



Peak force = PF, peak velocity = PV, peak power = PP, peak rate of force development = PRFD, impulse = IMP. Error bars represent + 1SD

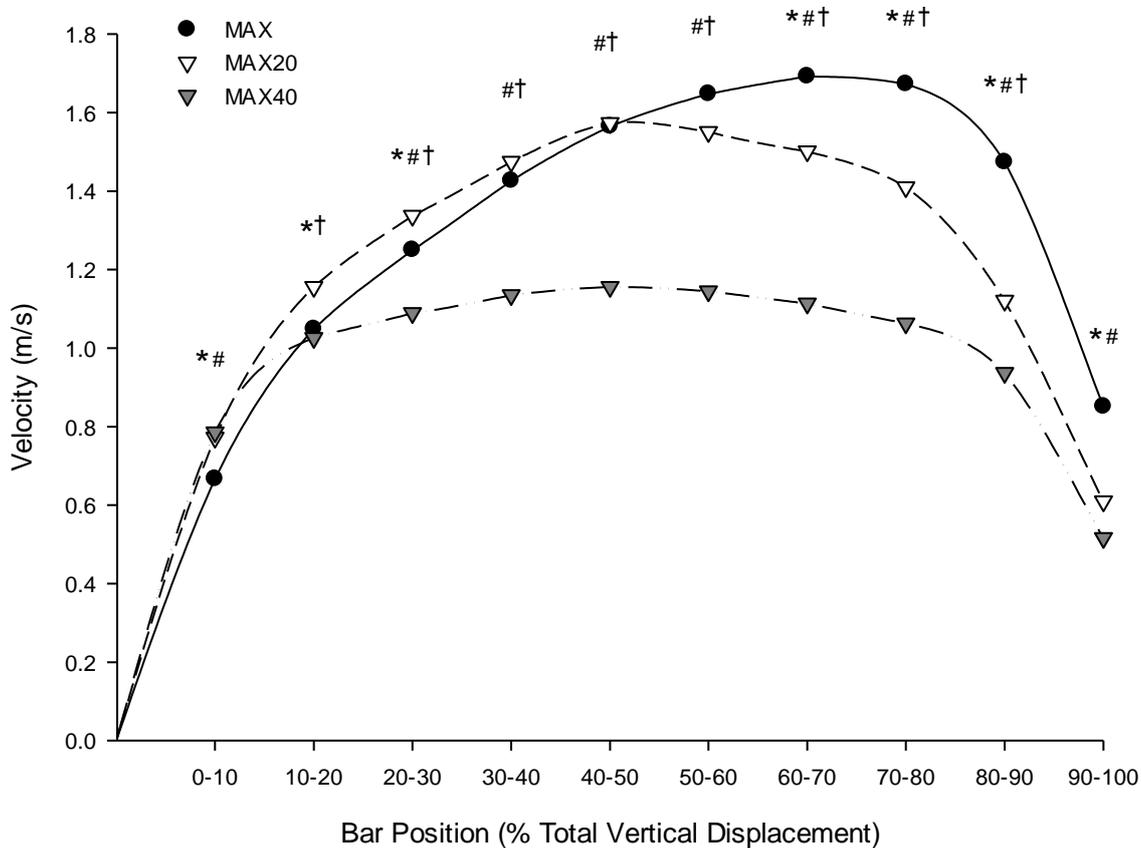
**Figure 7.3:** Mean vertical ground reaction forces during the concentric phase of MAX, MAX20, MAX40 conditions. Data are expressed as a percentage relative to the peak force value obtained.



\* Significant ( $p < 0.05$ ) difference between MAX and MAX20. # Significant ( $p < 0.05$ ) difference between MAX and MAX40. † Significant ( $p < 0.05$ ) difference between MAX20 and MAX40 for corresponding segment of movement.

The velocity of the barbell was also measured throughout the concentric action. Figure 7.4 shows mean values obtained during the 50% 1RM load for all 3 conditions. The results show that velocity of the barbell was significantly ( $p < 0.05$ ) greater when using chains during the very early stages of the movement, however, as the repetition progressed velocity with chain resistance decreased significantly below ( $p < 0.05$ ) that obtained with the constant barbell load.

**Figure 7.4:** Velocity during the concentric phase of maximum repetitions (MAX, MAX20, MAX40) with the 50% 1RM load. Values are averaged over 10% intervals of the vertical barbell displacement and interpolated to assist with comparison.



\* Significant ( $p < 0.05$ ) difference between MAX and MAX20 for corresponding segment of movement.  
 # Significant ( $p < 0.05$ ) difference between MAX and MAX40 for corresponding segment of movement.  
 † Significant ( $p < 0.05$ ) difference between MAX20 and MAX40 for corresponding segment of movement. Standard deviations across the ROM were similar between conditions and are illustrated on a selection of trials to maintain clarity.

#### **7.4.2 Study 2: A biomechanical comparison of straight and hexagonal barbell deadlifts**

No significant main effects of load were found for the orientation of the torso, hip, knee or ankle at the start of the concentric phase of the deadlift movement. Therefore, joint angles for the SBD and HBD were averaged across loads and are presented in Table 7.1. The pattern of movement at each joint was assessed by measuring joint angles over 10% intervals of the vertical barbell displacement. Statistical analyses revealed no significant main effects of load or barbell type for angles generated at the torso, hip or knee during the deadlift movement. A significant main effect of load was obtained at the ankle joint ( $p < 0.05$ ). The results showed that as load increased the maximum amount of ankle plantar flexion achieved at the conclusion of the concentric phase decreased.

**Table 7.1:** Joint angles at the starting position of the SBD and HBD averaged across loads (mean $\pm$ SD)

|     | Torso (°)      | Hip (°)         | Knee (°)         | Ankle (°)       |
|-----|----------------|-----------------|------------------|-----------------|
| SBD | 55.2 $\pm$ 9.8 | 89.8 $\pm$ 14.1 | 72.5 $\pm$ 13.7  | 28.2 $\pm$ 10.5 |
| HBD | 52.9 $\pm$ 9.8 | 91.8 $\pm$ 11.6 | 78.8 $\pm$ 11.2* | 29.1 $\pm$ 10.1 |

\* Significantly greater than corresponding condition ( $p < 0.05$ )

Significant main effects ( $p < 0.05$ ) were obtained for peak moments obtained at the lumbar spine, hip and knee when comparing the different barbells (Table 7.2). The results demonstrated that repetitions performed with the hexagonal barbell created significant increases in peak moments at the knee and significant decreases in peak moments at the lumbar spine and hip compared to repetitions performed with the straight barbell. These results were reflected in significant differences for the path of the barbells and corresponding resistance moment arms created (Figure 7.5 and Table 7.4). Significant main effects ( $p < 0.05$ ) following the same pattern for the joint moments, were also found for joint powers (Table 7.3). When these powers were summed across the joints, significantly greater values were found for the HBD compared with the SBD ( $p < 0.05$ ).

**Table 7.2:** Peak joint moments for the SBD and HBD across the loading spectrum

|  | <b>10%</b>       | <b>20%</b>       | <b>30%</b>       | <b>40%</b>       | <b>50%</b>       | <b>60%</b>       | <b>70%</b>       | <b>80%</b>       |
|--|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
|  | <b>1RM</b>       |
| <b>SBD Spine Peak Moment (N·m ±SD)</b> | 245.0<br>(46.3)* | 273.9<br>(52.6)* | 305.2<br>(54.1)* | 326.6<br>(61.2)* | 363.8<br>(67.4)* | 391.6<br>(70.4)* | 418.6<br>(70.7)  | 446.9<br>(73.9)  |
| <b>HBD Spine Peak Moment (N·m ±SD)</b> | 209.3<br>(48.6)* | 227.1<br>(54.1)* | 252.0<br>(60.8)* | 272.1<br>(70.7)* | 310.6<br>(84.7)* | 342.5<br>(89.4)* | 377.8<br>(92.3)  | 409.2<br>(98.3)  |
| <b>SBD Hip Peak Moment (N·m ±SD)</b>   | 205.5<br>(48.9)* | 225.2<br>(44.7)* | 251.2<br>(41.0)* | 267.6<br>(36.4)* | 298.9<br>(58.4)* | 321.0<br>(56.6)* | 338.7<br>(62.0)* | 353.0<br>(63.6)  |
| <b>HBD Hip Peak Moment (N·m ±SD)</b>   | 185.9<br>(30.2)* | 197.4<br>(30.7)* | 224.2<br>(33.6)* | 242.0<br>(38.0)* | 257.2<br>(37.5)* | 278.8<br>(50.0)* | 300.1<br>(53.9)* | 325.6<br>(59.4)  |
| <b>SBD Knee Peak Moment (N·m ±SD)</b>  | 74.5<br>(31.3)*  | 78.1<br>(33.2)*  | 80.4<br>(34.9)*  | 84.9<br>(36.0)*  | 87.5<br>(31.7)*  | 90.0<br>(29.7)*  | 92.1<br>(23.4)*  | 96.0<br>(17.8)*  |
| <b>HBD Knee Peak Moment (N·m ±SD)</b>  | 109.5<br>(34.8)* | 119.8<br>(41.8)* | 130.0<br>(48.6)* | 137.2<br>(49.1)* | 147.0<br>(47.8)* | 157.4<br>(41.2)* | 168.4<br>(53.9)* | 182.5<br>(56.6)* |
| <b>SBD Ankle Peak Moment (N·m ±SD)</b> | 138.3<br>(33.1)  | 155.1<br>(30.7)  | 177.9<br>(34.6)  | 194.7<br>(38.5)  | 204.8<br>(43.9)  | 215.4<br>(44.6)  | 229.4<br>(44.6)  | 232.8<br>(44.0)  |
| <b>HBD Ankle Peak Moment (N·m ±SD)</b> | 145.0<br>(25.4)  | 160.9<br>(24.9)  | 178.3<br>(31.9)  | 207.5<br>(34.8)  | 213.3<br>(37.3)  | 227.3<br>(43.4)  | 236.7<br>(51.8)  | 246.8<br>(59.4)  |

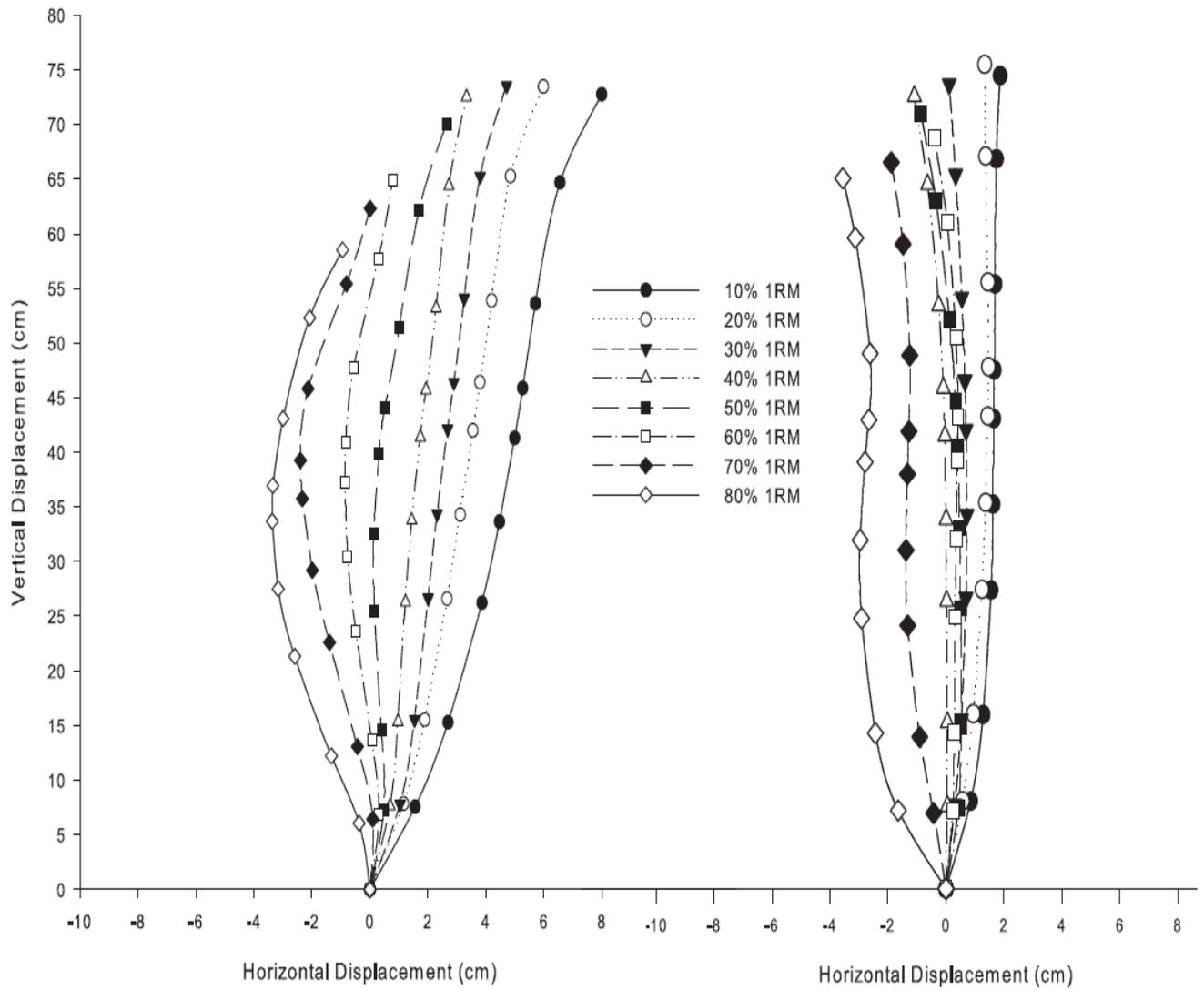
\* Significant difference between SBD and HBD for corresponding load (p<0.05).

**Table 7.3:** Peak joint powers for the SBD and HBD across the loading spectrum

|                                     | 10%                | 20%                | 30%                | 40%                | 50%                | 60%                | 70%                | 80%                |
|-------------------------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
|                                     | 1RM                |
| <b>SBD Spine Peak power (W ±SD)</b> | 260.7<br>(38.3)    | 299.5<br>(41.4)*   | 331.2<br>(44.5)*   | 347.3<br>(49.2)*   | 361.5<br>(55.1)*   | 350.0<br>(50.4)*   | 293.3<br>(39.8)*   | 269.7<br>(33.1)*   |
| <b>HBD Spine Peak power (W ±SD)</b> | 251.5<br>(31.3)    | 274.4<br>(40.5)*   | 262.3<br>(40.8)*   | 261.1<br>(38.9)*   | 233.2<br>(27.2)*   | 225.9<br>(29.6)*   | 228.8<br>(31.3)*   | 183.8<br>(19.5)*   |
| <b>SBD Hip Peak power (W ±SD)</b>   | 725.2<br>(148.1)*  | 805.8<br>(164.3)*  | 824.8<br>(157.0)*  | 756.6<br>(141.3)*  | 731.9<br>(139.4)*  | 698.6<br>(122.7)*  | 567.0<br>(114.3)*  | 446.9<br>(103.9)   |
| <b>HBD Hip Peak power (W ±SD)</b>   | 633.2<br>(120.2)*  | 690.9<br>(137.3)*  | 728.3<br>(139.1)*  | 660.7<br>(128.6)*  | 615.1<br>(117.9)*  | 527.3<br>(110.0)*  | 485.2<br>(103.4)*  | 424.9<br>(96.4)    |
| <b>SBD Knee Peak power (W ±SD)</b>  | 125.3<br>(68.4)*   | 122.0<br>(65.8)*   | 139.1<br>(64.5)*   | 125.2<br>(47.8)*   | 118.5<br>(40.4)*   | 106.4<br>(40.0)*   | 52.4<br>(29.1)*    | 36.1<br>(16.1)*    |
| <b>HBD Knee Peak power (W ±SD)</b>  | 224.8<br>(53.0)*   | 261.7<br>(55.3)*   | 294.9<br>(59.1)*   | 335.1<br>(65.2)*   | 421.4<br>(70.8)*   | 390.4<br>(66.3)*   | 311.5<br>(56.7)*   | 227.7<br>(40.4)*   |
| <b>SBD Ankle Peak power (W ±SD)</b> | 438.2<br>(120.4)*  | 486.0<br>(117.9)*  | 647.3<br>(147.6)*  | 661.8<br>(158.3)*  | 708.0<br>(171.6)*  | 773.8<br>(165.0)*  | 532.6<br>(140.1)*  | 312.2<br>(104.5)*  |
| <b>HBD Ankle Peak power (W ±SD)</b> | 647.9<br>(106.2)*  | 760.7<br>(114.5)*  | 926.1<br>(166.8)*  | 1133.0<br>(195.8)* | 1246.3<br>(201.6)* | 934.2<br>(190.4)*  | 725.0<br>(141.1)*  | 529.8<br>(100.7)*  |
| <b>SBD Sum Peak power (W ±SD)</b>   | 1549.9<br>(133.9)* | 1713.8<br>(159.2)* | 1942.5<br>(178.1)* | 1890.7<br>(170.5)* | 1919.0<br>(179.4)* | 1928.4<br>(168.6)* | 1445.9<br>(144.1)* | 1065.0<br>(103.6)* |
| <b>HBD Sum Peak power (W ±SD)</b>   | 1756.2<br>(142.4)* | 1986.5<br>(161.3)* | 2211.6<br>(181.4)* | 2389.8<br>(196.0)* | 2515.3<br>(207.9)* | 2076.3<br>(183.5)* | 1750.4<br>(149.2)* | 1365.4<br>(122.2)* |

\* Significant difference between SBD and HBD for corresponding load ( $p < 0.05$ ).

**Figure 7.5:** Barbell path during the SBD (left) and HBD (right) across the loading spectrum



**Table 7.4:** Resistance moment arms for the SBD and HBD averaged across loads

|            | <b>L5/S1 (cm)<br/>(±SD)</b> | <b>Hip (cm)<br/>(±SD)</b> | <b>Knee (cm)<br/>(±SD)</b> | <b>Ankle (cm)<br/>(±SD)</b> |
|------------|-----------------------------|---------------------------|----------------------------|-----------------------------|
| <b>SBD</b> | - 21.0 (3.0)*               | - 21.4 (3.8)*             | + 8.4 (2.4)*               | - 16.5 (2.1)*               |
| <b>HBD</b> | - 14.4 (3.0)*               | - 14.5 (2.6)*             | - 1.9 (0.8) *              | - 11.9 (1.8)*               |

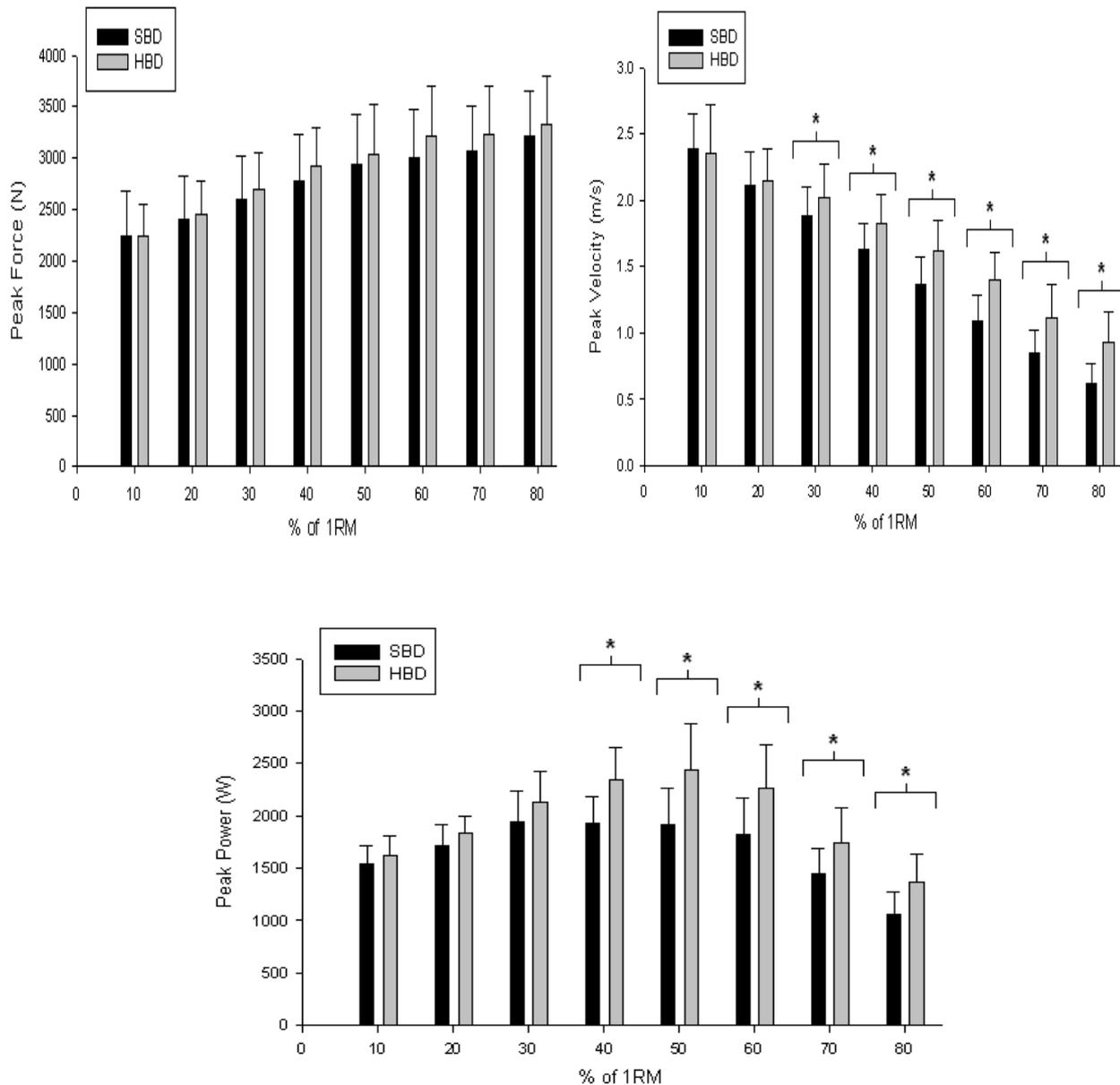
+ Direction of resistance moment arm creates extensor moment.

- Direction of resistance moment arm creates flexor moment.

\* Significant difference between SBD and HBD ( $p < 0.05$ ).

Each of the powerlifters that participated in the study lifted a heavier 1RM load in the HBD than the SBD resulting in an overall significant difference ( $265.0 \pm 41.8$  kg vs.  $244.5 \pm 39.5$  kg,  $p < 0.05$ ). Significant main effects of load and barbell type ( $p < 0.05$ ) were obtained for peak force, peak velocity and peak joint power summed at the lumbar spine, hip, knee and ankle (Figure 7.6). Significantly greater values were obtained for each of these variables when performing the HBD. A significant main effect of load was obtained for the relative time spent accelerating the resistance (Table 7.5).

**Figure 7.6:** Load-force, load-velocity and load-joint power relationships. \* Significant ( $p < 0.05$ ) difference between SBD and HBD for corresponding load. Error bars represent + SD.



**Table 7.5:** Relative time accelerating resistance during the SBD and HBD

|                     | 10%   | 20%   | 30%   | 40%   | 50%    | 60%   | 70%   | 80%    |
|---------------------|-------|-------|-------|-------|--------|-------|-------|--------|
|                     | 1RM   | 1RM   | 1RM   | 1RM   | 1RM    | 1RM   | 1RM   | 1RM    |
| <b>SBD Relative</b> | 59.7% | 62.2% | 67.3% | 70.5% | 75.1%  | 79.8% | 82.4% | 80.6%* |
| <b>Time (±SD)</b>   | (3.6) | (7.5) | (5.2) | (7.3) | (6.7)  | (8.8) | (6.0) | (4.3)  |
| <b>HBD Relative</b> | 59.1% | 61.6% | 65.0% | 70.3% | 74.6%  | 80.6% | 83.5% | 87.2%* |
| <b>Time(±SD)</b>    | (6.5) | (6.4) | (4.4) | (3.5) | (4.1)* | (5.8) | (5.1) | (4.1)  |

\* Significant difference between SBD and HBD for corresponding load ( $p < 0.05$ ).

## 7.5 Discussion

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The results from the two studies reported in this chapter demonstrate that variable resistance material and unconventional barbells can be used to enhance the biomechanical stimulus of a resistance exercise. The data obtained also support many of the anecdotal statements made previously by powerlifters regarding specific outcomes of each training practice. The following sections include discussion of the biomechanical effects measured and the potential for each training practice to enhance the stimulus associated with ERT.

The present study investigating the inclusion of chain resistance is the first to use combinations of barbell and chain loads of the magnitude commonly used and promoted by powerlifters. Previous studies investigating the effects of chain resistance have used comparatively much lighter chain loads than those used here. Ebben and Jensen (2002) substituted 10% of the barbell mass with chains during performance of the back squat with a 5RM load. Based on research equating a 5RM load with a resistance of 80% 1RM (Reynolds, Gordon and Robergs 2006), the chain mass substituted by Ebben and Jensen (2002) equalled approximately 8% of the athletes' 1RM. Lighter chain resistances have been used in studies investigating the biomechanics of weightlifting exercises. Coker and colleagues substituted only 5% of the participant's 1RM for chains during performance of the snatch (Coker, Berning and Briggs 2006) and power clean (Berning, Coker and Briggs 2008). Unsurprisingly, the studies conducted by Ebben and Jensen (2002) and Coker and colleagues (2008, 2006) reported no significant effects when substituting chains for any of the biomechanical variables measured. Baker and Newton (2009) were the first authors to include chain resistances approaching loads typically used by powerlifters. The experimental protocol compared a constant barbell resistance of 75% 1RM with a variable resistance that equalled 60% 1RM at the bottom of the movement and increased to a maximum 75% 1RM at half the total vertical displacement. The variable resistance was shown to develop significantly greater mean and peak velocity values compared with the constant barbell resistance. However, it is likely that the increase in velocity reported by Baker and Newton (2009) occurred at least in part because of the different average load lifted between conditions. In the variable resistance trials the combined chain and barbell load was less than the constant barbell resistance during the bottom half of the exercise and did not increase beyond the constant barbell resistance at any point during the

movement. As a result, the average load lifted was less in the variable condition and therefore an increase in movement velocity should be expected.

In the present study the average loads in the variable and constant resistance conditions were equated to investigate the effects of including chains without this confounding influence. Using this experimental protocol the results demonstrate that the inclusion of chains increases force and impulse, whilst concurrently reducing velocity, power and RFD (Figure 7.2). The reduction in peak and average velocity obtained with the inclusion of chains contradicts the previous findings reported by Baker and Newton (2009). Dissimilar results are most readily explained by the equating of average loads in the present study. Figure 7.4 illustrates that velocity in the MAX20 chain condition (load closest to that used by Baker and Newton (2009)) was greater than the constant barbell load until the overall resistances were of near equal magnitude. As the combined chain and barbell resistance continued to increase the velocity for the MAX20 chain condition fell below the comparison trial. Overall, the slower velocities obtained for the variable resistance during the second half of the movement must have exceeded the initial improvements to cause a reduction in average velocity. The negative effects on velocity during the variable resistance trials were greater in magnitude than the concomitant increase in force, explaining why average and peak power values were also reduced when chain resistance was included. The results of the present study also demonstrate that the combination of heavier chain and barbell loads resulted in greater relative increases in force and impulse, and greater relative decreases in velocity, power and RFD (Figure 7.2).

When the present study was conducted it was believed by most researchers and practitioners that resistance from chains and rubber bands provided the same effect. Simple models of both materials suggested that resistance increased linearly with displacement of the barbell. Subsequent work completed on the viscoelastic properties of rubber bands by McMaster et al. (2010) demonstrated that the length-tension relationship of rubber bands was best represented by quadratic polynomials where stiffness was at its greatest during the initial stage of elongation. However, it was generally expected that this non-linear feature would have minimal impact in distinguishing the biomechanical effects of bands and chains. On the basis of results obtained here and the large discrepancies between those reported by Winchester et al. (2005) for similar resistance with rubber bands, it became apparent that the dynamic properties of the resistance materials are distinct. At the same time, Arandjelović (2010) published equations of motion for bands and chains based on known

forces and the work-energy principle (derivation of the equations presented by Arandjelović (2010)) are displayed in appendix III, and appear in their explicit form in equation 7.1 and 7.2 below). The equations of motion presented by Arandjelović (2010) for bands and chains were shown to be fundamentally different. For a given amount of force, the acceleration when including bands is limited by the mass of the barbell, and the stiffness and displacement of the bands. In contrast, when including chains the acceleration is limited by the mass of the chains, the mass of the barbell and the square of the system velocity. The different mechanical effects exhibited by bands and chains in the dynamic case can be explained by the different inertial properties of the materials. Rubber bands have negligible mass and therefore contribute to resistance through stiffness and displacement of the material only. In contrast, chains provide a substantial mass element that creates resistance by gravitational acceleration and through change in momentum which occurs when individual links are accelerated to the velocity of the barbell from initial stationary positions (Arandjelovic 2010). Based on the different equations of motion established by Arandjelović (2010), it is expected in circumstances where the static properties of bands and chains are matched that the acceleration and therefore velocity of the movement will be slower when including chains.

$$\ddot{z}_1 = \frac{F - kz}{m} - g. \quad (\text{eq7.1})$$

$$\ddot{z}_2 = \frac{F - \frac{1}{2}\alpha z^2}{m + \alpha z} - g. \quad (\text{eq7.2})$$

Where,  $\ddot{z}_1$  is the acceleration of the barbell with rubber bands attached,  $\ddot{z}_2$  is the acceleration of the barbell with chains attached, F is the vertical ground reaction force, m is the mass of the barbell, g is the acceleration due to gravity, z is vertical position off the ground, k is the stiffness of the rubber band and  $\alpha$  is the mass per unit length of the chains.

The altered dynamics that chains impose when they are attached to the barbell could explain the biomechanical differences obtained in the present study. The sub-maximum loads used in the experimental protocol would have enabled relatively fast velocities to be produced in the early stages of the movement. These fast velocities and subsequent large

changes in momentum of the chain links would immediately act to slow the barbells ascent. (see equation 7.2). As a result, this mechanism may explain the reduced average and peak velocity values obtained when chain resistance was included. Additionally, when comparing the velocity of the different chain conditions throughout the range of motion it is evident that the mass of the chains had an important effect (Figure 7.4). The equation of motion derived for the combined barbell and chain system shows that the velocity term which detracts from the acceleration is multiplied by a coefficient equal to the mass per unit length of the chain (see equation 7.2). This feature of the dynamics is likely to explain why velocity with the heavier chain resistance (MAX40) fell substantially below the lighter condition (MAX20) even during the first half of the movement when the total resistance was less. Increases in peak force measured during repetitions with chains may also be due to the decrease in movement velocity and the well established inverse relationship that exists between the two variables (Cronin, McNair and Marshall 2003, Rahmani et al. 2001). However, it is likely that greater absolute loads lifted during the second half of the movement when including chains also contributed to increases in peak forces measured.

The present study was the first to test the theory that the inclusion of chain resistance with a traditional resistance exercise enables greater force production to be maintained during the latter stages of the concentric action. The results confirmed the theory and illustrated that greater relative forces were maintained when heavier chains resistances were included. This single finding may suggest that the inclusion of chain resistance could be used to enhance the stimulus created when a traditional resistance exercise is combined with ERT. However, the concurrent large reductions in velocity, power and RFD values obtained when chain resistance was included indicate that this is unlikely to be the case. Interestingly, when the athletes in the present study were asked if they perceived any difference in performance with the inclusion of chains, the majority believed that repetitions were faster and more explosive with chain resistance. At present it is not clear why there is such a discrepancy between the actual and perceived performances.

In contrast to the mixed findings with the inclusion of chain resistance, the results from study two presented in this chapter, demonstrated that the unconventional hexagonal barbell could be used to enhance the majority of variables analysed. Differences obtained between deadlifts performed with the straight and hexagonal barbell are explained by changes in position of the external resistance relative to segments of the body. At the beginning of the movement the resistance was positioned closer to the athletes (as measured by the horizontal distance between the load and ankle joint centre) when using

the hexagonal barbell. The different positioning of the load at the start of the exercise significantly affected the initial knee angle resulting in greater flexion with the HBD. Using the starting position of the load as a reference point, the hexagonal barbell reduced horizontal displacement away from the body by an average of 75% compared to the straight barbell (Figure. 7.5). For loads greater than 60% 1RM, the hexagonal barbell increased displacement towards the body by an average of 22%. The change in positioning of the load due to the design of the hexagonal barbell significantly reduced moment arms of the resistance at all joints across the loads (Table 7.4). As a result, peak moments developed at the lumbar spine, hip and ankle during the HBD were significantly lower than that developed during the SBD (Table 7.2). In contrast, the peak moment at the knee was significantly increased when performing the HBD, despite the reduction in the magnitude of the resistance moment arm. This result is explained by the different direction of the resistance moment created. During the SBD the load remained in front of the knee and created an extension moment that reduced the muscular effort required to extend the joint. Conversely, during the HBD the load remained behind knee for the majority of the movement and created a flexor moment that increased the muscular effort and subsequent peak moment.

The ability to manipulate joint moments based on selection of a barbell provides relevant information for strength and conditioning coaches. For contemporary powerlifters the evidence obtained here supports their use of unconventional barbells to alter mechanical stress and potentially target specific areas of the body that are believed to limit individual performances. The particular case investigated in the present study provides relevant information regarding the important lumbar area. The conventional deadlift performed with heavy loads is commonly viewed as the most challenging and appropriate exercise to develop the muscles around the lumbar spine (Cholewicki, McGill and Norman 1991). The results of this study confirm that the SBD can be used to produce very large net joint moments at the L5S1 joint and should be performed if the training goal is to target the lumbar area. In contrast, the HBD results in a more even distribution of the load across the joints of the torso and lower extremities. Therefore, strength and conditioning coaches searching for an alternative to the squat may find the HBD to be an effective alternative with both exercises exhibiting similar joint moment profiles (Flanagan and Salem 2008). For individuals with a history of lower back pain or currently in the final stages of rehabilitation, performing the deadlift with the hexagonal barbell rather than the straight barbell may be a more prudent strategy to recruit the lumbar area whilst more evenly distributing the load between the joints of the body.

The comparison between the SBD and HBD clearly demonstrates the potential for unconventional barbells to enhance the stimulus of ERT. The results show that performing the deadlift with the hexagonal barbell resulted in significantly greater values for peak force, peak velocity, peak joint power and RFD. The increased values are likely to be the result of a more even distribution of the load and improved ability to accelerate the resistance due to its positioning. In additional work published from this thesis, it was shown that similar improvements in force, velocity, power and RFD could be obtained when weighted vertical jumps were performed with the hexagonal barbell held at arms' length compared to a straight barbell positioned across the posterior shoulder girdle (Swinton et al. 2010b). At present it is not known whether these improvements in the biomechanical stimulus are restricted to the hexagonal barbell or whether other unconventional barbells can offer similar advantages. Further research should be conducted to gain a better understanding of the effects of altering the spatial relationship between body segments and resistance to assess best practice.

An extensive research effort has been devoted to identifying loads that maximise power due to the belief that these are the most effective resistances to train with (Cronin and Sleivert 2005) However, some researchers have commented that effective resistances are likely to cover a range of loads that may depend on the specific phase of an athlete's development (Frost, Cronin and Newton 2008). As discussed in chapter six, it has been recommended that researchers avoid calculating power from the product of the GRF and the barbell velocity as this method may not reflect the actual power generated (Lake, Lauder and Smith 2012). Instead it was recommended that power be calculated from direct integration of the GRF data and knowledge of the system mass, or through inverse dynamics and the calculation of net joint power (Lake, Lauder and Smith 2012). In the present study, power was measured using both internal and external calculations with values summed for the torso, hip, knee and ankle for the former. The results demonstrated for both methods that maximum peak power values were produced with 30% 1RM for the SBD and 50% 1RM for the HBD. A similar increase in load that caused maximum peak power values was found in our study comparing weighted jumps performed with the straight or hexagonal barbell (Swinton, Agouris, et al. 2010b). At present, it is not clear what factors caused the shift in the load-power relationship, however, it may be speculated that the greater maximum resistance that can be lifted with the hexagonal barbell was influential.

## 7.6 Summary and Conclusion

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The studies presented in this chapter have demonstrated that two of the most popular training practices used by contemporary powerlifters have the potential to substantially alter the biomechanical stimulus of an exercise. Combining information from recent research and the results reported here demonstrate that the biomechanical stimulus created when incorporating either chains or rubber bands can be very different. Despite results illustrating that chains can be used to maintain high levels of force throughout the exercise movement, the data also show that heavy chain resistance has a negative effect on a range of variables believed to be important for adaptations with ERT. In contrast, additional resistance in the form of rubber bands has been shown in other studies to maintain high levels of force whilst increasing velocity power and RFD. Therefore, it is suggested that powerlifters and general athletes could benefit from including rubber bands with exercises used when performing ERT. Whereas, chain resistance may be better suited to training aimed at increasing maximum strength where reduced resistance is created during the sticking region and subsequently increases to match the mechanical advantage of the lifter towards the end of the movement.

The second study presented in this chapter highlighted that change in the position of the external resistance through the use of an unconventional barbell has the potential to alter a wide range of internal and external kinematics and kinetics. Importantly, the results expand on those from the previous chapter demonstrating that the biomechanical stimulus created with a traditional resistance exercises such as the deadlift can be further enhanced for ERT. Additionally, the specific results obtained with the hexagonal barbell deadlift suggest that the exercise could be an effective variation for the squat and may be appropriate to use in the final stages of low back rehabilitation.

## CHAPTER 8. ALTERING MOVEMENT STRATEGIES

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### 8.1 Prelude

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As highlighted in chapter three, a substantial portion of the information disseminated regarding contemporary powerlifting training is devoted to optimising technique in the squat, bench press and deadlift. For each exercise a number of key technical points have been proposed to create a favourable balance between the external resistance and the internal force production capabilities of the body. In general, these technical points refer to common postures which should be adopted at critical points during the movement. Of the three competition exercises the majority of technique related information disseminated by powerlifters has focused on the squat. Almost all technical recommendations for the exercise feature a movement strategy which is commonly referred to as sitting back. The key technical feature of this strategy is to maintain as vertical a shin position as possible throughout the entire movement. The overall pattern that emerges from this constraint appears to be very different from that observed during traditional squatting movements. It is widely advocated that powerlifters learn the movement by first performing the box squat which provides assistance with maintaining balance. Additionally, the box squat itself is promoted as an effective exercise to combine with ERT to enhance athleticism. The purpose of this chapter is to compare the biomechanical stimulus created during a traditional squatting motion with that created during the movement strategy recommended by powerlifters (with and without a box). The results of the study will provide novel information for individuals considering adopting the squatting practices promoted by powerlifters in attempts to enhance performance and athleticism.

## 8.2 Introduction

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The squat is one of the most widely utilised resistance exercises for strength development in both athletic and rehabilitation settings. As a result of its widespread use, the exercise has been the focus of a large number of biomechanical studies (McLaughlin, Lardner and Dillman 1978, McBride et al. 2010, Escamilla et al. 2001b, Fry, Smith and Schilling 2003, Escamilla et al. 2001a). The results present the squat as a complex movement which requires coordinated actions of the torso and all major joints of the lower extremities. Furthermore, this complexity enables individuals to select different movement strategies to perform the exercise. From a performance enhancement and injury risk perspective, it is commonly recommended that movement strategies used to perform the squat should seek to minimise anterior displacement of the knee (Chandler and Stone 1991). In particular, it is most frequently stated that individuals should avoid displacing the knee past the toes. This recommendation is based on findings that restricting anterior displacement reduces internal forces at the knee and emphasises recruitment of the hip extensor muscles (Chandler and Stone 1991, Chiu, Heiler and Sorenson 2009).

The first study to investigate the effects of controlling anterior knee displacement during the squat was conducted Fry et al. (2003). The investigators measured joint torques produced at the hip and knee when squats were performed under two conditions with differing amounts of knee displacement. During the first condition participants were instructed to displace the knee beyond the toes, whereas, during the second condition displacement was restricted by placing a perpendicular vertical board immediately anterior to the participants' toes. Restricting anterior displacement was shown to produce lower torques at the knee and greater torques at the hip in comparison to the unrestricted movement. The authors also reported that restricting anterior displacement of the knee created a more horizontal torso position, which was suggested to indicate greater shear forces were developed at the lumbar spine. The authors proposed that participants adopted an increased horizontal posture to compensate for changes in positioning of the lower leg and to maintain the system COM over the base of support. The results obtained by Fry et al. (2003) have caused some to propose that restricting anterior displacement of the knee during squatting may create potentially injurious forces at the lower back (Chiu, Heiler and Sorenson 2009).

Restricting displacement of the knee is a key feature of the squatting technique promoted by powerlifters. However, instead of proposing that the knee remain posterior to the toes,

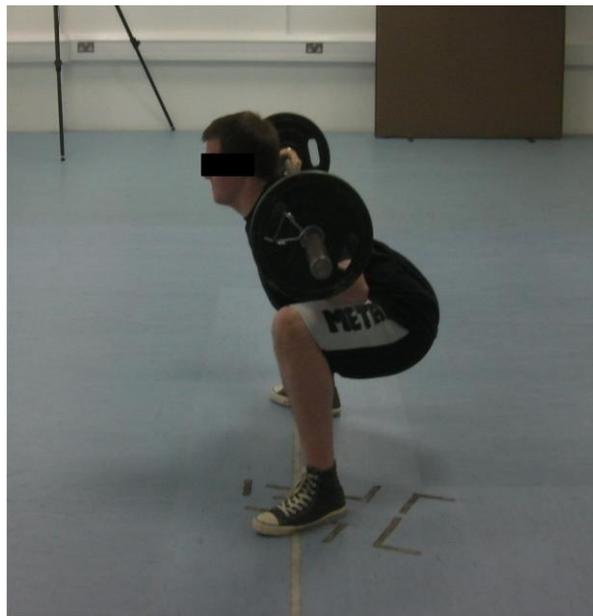
many powerlifters recommend zero displacement of the knee whilst maintaining a vertical shin position throughout the entire movement (Simmons 2003). To achieve this technique, many powerlifters adopt a wide stance and focus on moving the hips posteriorly during the descent phase of the movement. In practical settings, this movement strategy is often referred to as “sitting back” and is the main feature of what is considered to represent the powerlifting squat (Hales, Johnson and Johnson 2009, Chiu, Heiler and Sorenson 2009) (Figure 8.1). It is important to note that whilst this technique is considered to represent a distinct exercise from the traditional squat (Hales, Johnson and Johnson 2009), it may be more accurate to consider the two movements to represent opposite ends of a spectrum. However, the convention of referring to the powerlifting technique as a separate exercise will be adopted for this chapter.

The majority of powerlifters choose to perform the powerlifting squat in training and in competition as they believe the movement strategy enables the heaviest load to be lifted (Simmons 2003). Mechanisms used to explain the assumed advantage include a reduction in vertical displacement requiring less mechanical work, and more effective distribution of the resistance with stress being transferred from the knee and ankle to the hip and lower back (Simmons 2003). In addition, some powerlifters have suggested that this style of squatting creates similar mechanical demands to the deadlift, which may enable training aimed at one exercise to cross over and improve the other (Tate 2006). However, a recent study comparing the kinematics of the squat and deadlift during a single powerlifting competition indicated that the movements exhibit distinct profiles and therefore a direct cross-over effect was considered unlikely (Hales, Johnson and Johnson 2009).

In contrast to previous findings suggesting that reduced knee displacement creates a more inclined torso position (Fry, Smith and Schilling 2003), observation of skilled powerlifters reveals that many individuals can maintain a near vertical shin position whilst adopting relatively upright postures. At present, is not fully understood how these individuals successfully perform this task. However, to develop proficiency in the movement it is recommended that powerlifters perform the box squat in training (Tate, 2006, Simmons 2003) (Figure 8.1). The additional apparatus enables the performer to maximise posterior displacement of the hip and maintain a vertical shin position by acting as a safety device to catch the individual if the COM is moved behind the base of support. Additionally, the box squat has also been recommended for general athletes to increase lower body strength and RFD (Brown, Nitka and Pyka 1998, Brown, Shepard and Sjostrom 2003).

Based on recommendations by powerlifters and recent large improvements in world best performances, both the powerlifting squat and box squat are now popular exercises used by general athletes to develop strength and power (McBride et al. 2010, Chiu, Heiler and Sorenson 2009). However, some researchers and practitioners have questioned the safety and effectiveness of both exercises (Chiu, Heiler and Sorenson 2009, Brown, Shepard and Sjostrom 2003). To date, only a limited number of studies have quantified biomechanical variables during the powerlifting squat or box squat. Multiple investigators have collected data from squats performed during powerlifting competitions (McLaughlin, Dillman and Lardner 1977, Escamilla et al. 2001a), however, research has established that techniques used are highly variable, with some competitors selecting more traditional movement patterns (Hales, Johnson and Johnson 2009). Less information is available regarding the biomechanics of the box squat. McBride et al. (2010) compared kinetic and EMG data of powerlifters performing the exercise and what was described as a standard squatting movement. The authors reported that the inclusion of the box had minimal effect and similar values for force, power and muscle activity measured at the thigh were obtained. The experimental protocol utilised by Mc Bride et al. (2010) did not calculate joint specific data or provide kinematic information regarding the movement strategies used by the powerlifters to perform each exercise. Due to the limited information available at present, coaches and athletes are unable to make informed judgements regarding the appropriateness of the powerlifting squat or box squat. Therefore, it was the aim of this study to provide detailed kinematic and kinetic comparisons of the different techniques, with the traditional squat used as a reference. In fulfilling this aim, the study objectives included data collection for each exercise over a range of loads performed with the intent to overcome the load as fast as possible to simulate the training protocols used frequently to develop muscular strength and power.

**Figure 8.1:** Traditional Squat (top left), Powerlifting Squat (top right) and Box Squat



## 8.3 Methods

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### Experimental Approach to the Problem

A cross-sectional, repeated measures design was used to quantify and compare kinematics and kinetics of the traditional squat, powerlifting squat and box squat. The experimental approach provided original information regarding movement strategies used to perform each exercise and comparative data to assist practitioners in exercise instruction and training prescription. The participants comprised well-trained powerlifters with extensive experience in performing each exercise. Data were collected for each participant over two sessions separated by one week. Session 1 was performed in the gymnasium and involved 1RM testing in the squat. Session 2 was performed in the laboratory where participants performed maximum speed repetitions for each exercise using loads of 30, 50 and 70% of their recorded 1RM. Kinematics and kinetics were analysed during session 2 only.

### Participants

Twelve male powerlifters participated in the study (age:  $27.2 \pm 4.2$  yr; stature:  $180.3 \pm 4.8$  cm; mass:  $100.2 \pm 13.1$  kg; squat 1RM:  $220.2 \pm 36.2$  kg; resistance training experience:  $9.2 \pm 3.1$  yr). All participants had a minimum of 3 yrs experience performing each exercise. The study was conducted three months after a regional competition where the majority of athletes were nearing the end of a training cycle aimed at matching or exceeding their previous competition performance. Participants were notified about the potential risks involved and gave their written informed consent to be included. Prior approval was given by the ethical review panel at Robert Gordon University, Aberdeen, UK.

### 1RM testing

All participants chose to perform the squat 1RM test using the powerlifting technique they used in competition. No supportive aids beyond the use of a weightlifting belt were permitted during the test. Based on a 1RM load predicted from performance in recent training sessions participants performed a series of warm-up sets and up to 5 maximum attempts. A minimum of 2 minutes and a maximum of 4 minutes recovery time were allocated between attempts. Within this time frame participants chose to perform the lifts based on their own perception of when they had recovered. All repetitions were performed

to a depth where the thighs became parallel with the floor. Each attempt was deemed successful if the appropriate depth was reached and the barbell was not lowered at any point during completion of the ascent phase.

### **Squat variation testing**

Prior to performing maximum speed repetitions participants engaged in their own specific warm-up. Generally, this began with 3 to 5 sets of light squats (e.g. < 40% 1RM) for 6 to 10 repetitions. Individuals then performed a series of maximum speed repetitions prior to any data collection. Once suitably prepared, participants performed all three exercises with loads of 30, 50, and 70% of their predetermined 1RM. One trial comprising two repetitions was performed for each load and condition to assess intra-trial reliability. The nine trials were performed in a randomised order with a minimum 2 minute rest period allocated. A longer rest period of up to 4 minutes was made available if the participant felt it necessary to produce a maximum performance. Instructions were given during the traditional squat to allow the knee to travel past the toes during the descent phase. For the powerlifting squat and box squat instructions were given to move the hip posteriorly and to maintain as vertical a shin position as possible. During the box squat participants were permitted to displace the COM behind the base of support during the final portion of the descent and were instructed to pause for a minimum of 1 second on the box. Instructions were given to perform the concentric portion of each repetition with maximum effort attempting to lift the load as fast as possible whilst maintaining contact with the ground throughout the movement. For each trial the repetition that produced the greatest peak barbell velocity was selected for further analysis.

### **Biomechanical Analyses**

The squat variation trials were performed with a separate piezoelectric force platform (Kistler, Type 9281B Kistler Instruments, Winterthur, Switzerland) under each foot, in a capture area defined by a nine-camera motion analysis system (Vicon MX, Vicon Motion Systems, Oxford, UK). Marker position and ground reaction force data were captured at 200 and 1200Hz respectively. Based on a frequency content analysis of the three-dimensional coordinate data, marker trajectories were filtered using a digital fourth-order low-pass Butterworth filter with a cut-off frequency of 6 Hz. Internal kinematics and kinetics were calculated using the models presented in chapter five. Instantaneous velocities and

accelerations were calculated by numerical differentiation of the position data (Hildebrand 1974). Kinematic and kinetic measures for the hip, knee and ankle were calculated for both left and right sides and averaged to obtain single values. The starting point for each trial was defined as the point where the centre of the barbell began its descent. The beginning of the concentric phase was demarcated as the first frame after the barbell reached its lowest elevation. The end of the concentric phase was defined as the point where the barbell reached maximum vertical elevation. Squatting technique was assessed by using quantitative and qualitative means. Quantitatively, technique was assessed by measuring joint angles during the first frame of the concentric movement. For qualitative analyses representative joint angle-time curves were selected and compared across techniques. Similar quantitative and qualitative analyses have been used previously to describe techniques used to perform the squat (Fry, Smith and Schilling 2003, Escamilla et al. 2001a) Peak net joint moments and RFD values were calculated to assess the potential effectiveness of each exercise for ERT. RFD was calculated from the slope of the vertical GRF-time curve extending from the transition between eccentric and concentric phases to the maximum value of the first peak.

### **Statistical Analysis**

Intra-trial reliability for each variable analysed was assessed by ICC. As recommended by Baumgartner (2006), ICCs were calculated with a correction factor for number of repetitions performed per trial ( $n = 2$ ) and number of repetitions used in the criterion score ( $n = 1$ ). Intra-trial reliability for all variables reported was above 0.88. Potential differences in kinematic and kinetic variables measured during the squats were analysed using a 3x3 (squat type x load) repeated measures ANOVA. Significant main effects were further analysed with Bonferroni adjusted pair-wise comparisons. Statistical significance was accepted at  $p < 0.05$ . All statistical procedures were performed using the SPSS software package (SPSS, Version 17.0, SPSS Inc., Chicago, IL).

## 8.4 Results

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### Linear Kinematics

The powerlifting squat and box squat were performed with a significantly wider stance than the traditional squat ( $89.6 \pm 4.9\text{cm}$ ,  $92.1 \pm 5.1\text{cm}$ ,  $48.3 \pm 3.8\text{cm}$ , respectively). Linear displacements of the barbell and joint centres in the anterior-posterior direction revealed differences across techniques (Table 8.1). The largest effects were noted during the eccentric phase where greater posterior hip displacements and reduced anterior knee displacements occurred during the powerlifting squat and box squat compared to the traditional squat. These differences were reflected in the overall displacement of the system COM. During the eccentric phase the system COM was displaced anteriorly during the traditional squat and posteriorly during the powerlifting squat and box squat.

### Angular Kinematics

Potential differences in squatting posture were primarily assessed by recording segmental angles during the first frame of the concentric phase. The values were averaged across loads as the external resistance was found to have minimal effect (Table 8.2). Similar torso angles were obtained for the traditional squat and powerlifting squat. However, at the start of the concentric phase a significantly more upright torso was recorded for the box squat. Angular differences across the exercises were observed at all three joint axes of the hip. The wide stance squats (powerlifting and box) displayed significantly greater abduction angles than the traditional squat. In addition, significantly greater hip flexion and internal rotation was recorded during the powerlifting squat compared with the other exercises. Significant differences were also obtained for the knee and ankle, with greater flexion angles obtained at both joints during the traditional squat.

**Table 8.1:** Anterior-posterior displacements calculated across the eccentric and concentric phases (mean  $\pm$  SD)

|                   |                  | Traditional       | Powerlifting      | Box               |
|-------------------|------------------|-------------------|-------------------|-------------------|
| <b>Eccentric</b>  | <b>30% 1RM</b>   |                   |                   |                   |
|                   | Bar (cm)         | 9.5 $\pm$ 2.1*†   | 5.1 $\pm$ 2.2*‡   | -6.8 $\pm$ 6.0†‡  |
|                   | COM (cm)         | 3.2 $\pm$ 2.8*†   | -6.8 $\pm$ 3.1*   | -8.4 $\pm$ 3.5†   |
|                   | Hip (cm)         | -15.5 $\pm$ 2.6*† | -21.1 $\pm$ 3.2*‡ | -28.7 $\pm$ 5.1†‡ |
|                   | Knee (cm)        | 22.4 $\pm$ 4.3*†  | 16.4 $\pm$ 3.3*‡  | 13.9 $\pm$ 2.7†‡  |
|                   | <b>50% 1RM</b>   |                   |                   |                   |
|                   | Bar (cm)         | 8.4 $\pm$ 1.8*†   | 4.1 $\pm$ 2.2*‡   | -7.1 $\pm$ 6.4†‡  |
|                   | COM (cm)         | 3.5 $\pm$ 2.7*†   | -4.2 $\pm$ 3.0*   | -7.9 $\pm$ 4.0†   |
|                   | Hip (cm)         | -15.6 $\pm$ 1.8*† | -18.1 $\pm$ 2.9*‡ | -25.3 $\pm$ 6.2†‡ |
|                   | Knee (cm)        | 20.7 $\pm$ 3.1†   | 17.3 $\pm$ 4.1‡   | 14.4 $\pm$ 3.5†‡  |
|                   | <b>70% 1RM</b>   |                   |                   |                   |
|                   | Bar (cm)         | 7.4 $\pm$ 1.8*†   | 3.8 $\pm$ 1.9*‡   | -5.9 $\pm$ 2.9†‡  |
| COM (cm)          | 4.1 $\pm$ 3.4*†  | -2.8 $\pm$ 2.4*   | -3.7 $\pm$ 3.2†   |                   |
| Hip (cm)          | -15.1 $\pm$ 2.7† | -16.0 $\pm$ 6.2‡  | -23.6 $\pm$ 6.0†‡ |                   |
| Knee (cm)         | 19.9 $\pm$ 2.6†  | 18.2 $\pm$ 5.0‡   | 13.7 $\pm$ 3.9†‡  |                   |
| <b>Concentric</b> | <b>30% 1RM</b>   |                   |                   |                   |
|                   | Bar (cm)         | -5.8 $\pm$ 2.1†   | -4.2 $\pm$ 2.2‡   | 9.4 $\pm$ 4.1†‡   |
|                   | COM (cm)         | -2.5 $\pm$ 1.2*†  | 6.7 $\pm$ 2.3*‡   | 10.6 $\pm$ 2.9†‡  |
|                   | Hip (cm)         | 18.1 $\pm$ 3.4†   | 20.2 $\pm$ 2.8‡   | 29.0 $\pm$ 3.3†‡  |
|                   | Knee (cm)        | -21.6 $\pm$ 4.1*† | -18.2 $\pm$ 3.1*‡ | -13.1 $\pm$ 2.5†‡ |
|                   | <b>50% 1RM</b>   |                   |                   |                   |
|                   | Bar (cm)         | -6.2 $\pm$ 1.9*†  | -3.6 $\pm$ 2.4*‡  | 10.8 $\pm$ 3.7†‡  |
|                   | COM (cm)         | -2.0 $\pm$ 0.8*†  | 7.6 $\pm$ 1.6*‡   | 11.3 $\pm$ 2.2†‡  |
|                   | Hip (cm)         | 16.2 $\pm$ 3.1*†  | 19.2 $\pm$ 1.9*‡  | 29.0 $\pm$ 3.4†‡  |
|                   | Knee (cm)        | -22.8 $\pm$ 4.2*† | -18.3 $\pm$ 3.2*‡ | -13.3 $\pm$ 2.3†‡ |
|                   | <b>70% 1RM</b>   |                   |                   |                   |
|                   | Bar (cm)         | -6.1 $\pm$ 1.9†   | -3.7 $\pm$ 2.7‡   | 9.9 $\pm$ 4.0†‡   |
| COM (cm)          | -2.0 $\pm$ 0.8*† | 8.4 $\pm$ 5.0*    | 9.5 $\pm$ 1.8†    |                   |
| Hip (cm)          | 14.7 $\pm$ 3.3†  | 17.5 $\pm$ 2.0‡   | 26.6 $\pm$ 3.1†‡  |                   |
| Knee (cm)         | -20.3 $\pm$ 3.6† | -19.2 $\pm$ 3.2‡  | -13.7 $\pm$ 3.4†‡ |                   |

\* Significant difference between traditional and powerlifting ( $p < 0.05$ )

† Significant difference between traditional and box ( $p < 0.05$ )

‡ Significant difference between powerlifting and box ( $p < 0.05$ )

**Table 8.2:** Joint angles at the start of the concentric phase (mean  $\pm$  SD)

|                      | <b>Traditional</b> | <b>Powerlifting</b> | <b>Box</b>        |
|----------------------|--------------------|---------------------|-------------------|
| Torso (flexion °)    | 33.5 $\pm$ 4.6†    | 33.1 $\pm$ 4.5‡     | 26.9 $\pm$ 3.8†‡  |
| Hip (flexion °)      | 104.3 $\pm$ 4.9*   | 112.6 $\pm$ 5.8*    | 105.7 $\pm$ 5.6   |
| Hip (abduction°)     | 28.0 $\pm$ 5.5*†   | 38.4 $\pm$ 4.7*     | 37.5 $\pm$ 2.2†   |
| Hip (int rotation °) | 19.3 $\pm$ 3.3*    | 27.4 $\pm$ 4.1*‡    | 20.9 $\pm$ 2.1‡   |
| Knee (flexion °)     | 121.1 $\pm$ 3.4*†  | 112.1 $\pm$ 4.3*‡   | 103.8 $\pm$ 5.2†‡ |
| Ankle (flexion °)    | 37.2 $\pm$ 3.9*†   | 26.7 $\pm$ 5.1*‡    | 14.4 $\pm$ 4.2†‡  |
| Shank (horizontal°)  | 53.2 $\pm$ 3.1*†   | 68.9 $\pm$ 4.1*‡    | 76.3 $\pm$ 3.8†‡  |

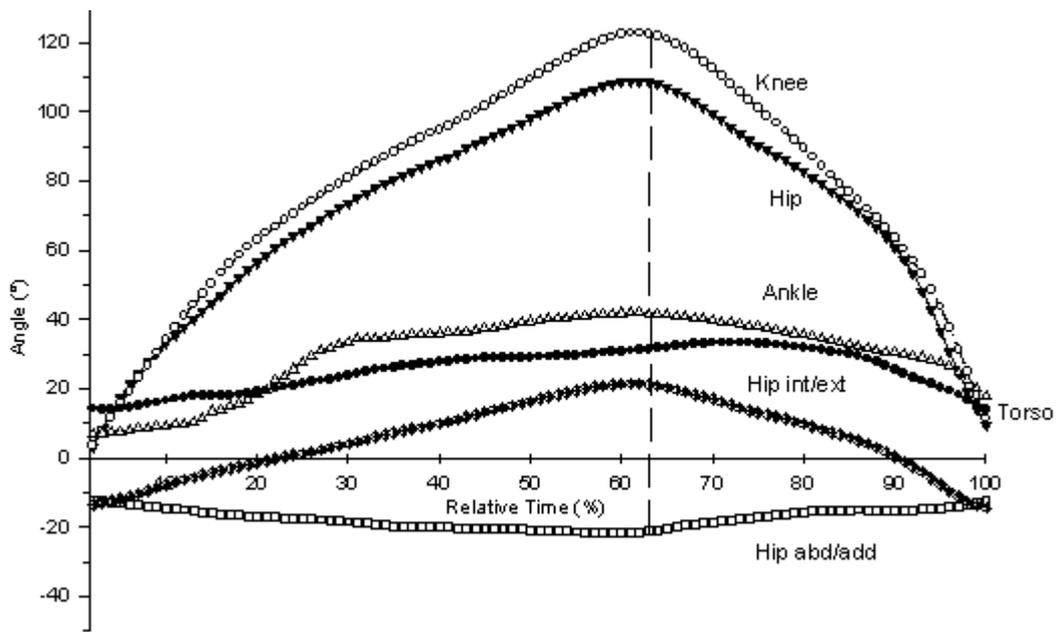
\* Significant difference between traditional and powerlifting ( $p < 0.05$ )

† Significant difference between traditional and box ( $p < 0.05$ )

‡ Significant difference between powerlifting and box ( $p < 0.05$ )

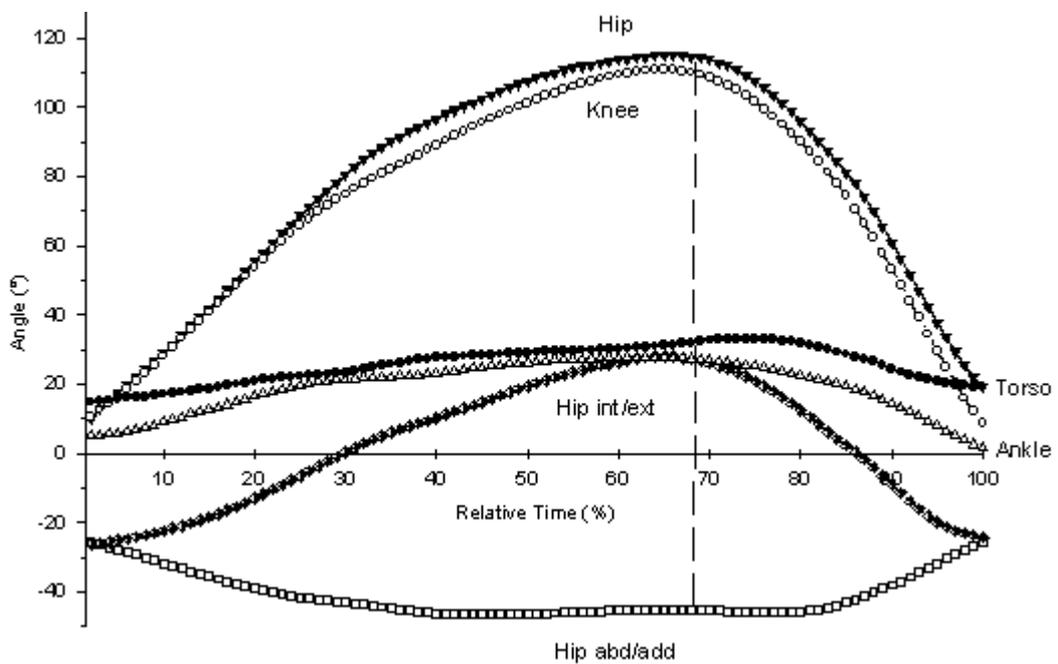
A qualitative assessment of the lifting technique adopted for each exercise was obtained by selecting representative joint angle-time curves. Comparatively homogenous traces were obtained for the traditional squat (Figure 8.2). The results illustrate that the hip and knee flex and extend together with similar magnitudes. Also, similar patterns of flexion then extension were observed for the torso and ankle during the traditional squat. Assessment of the joint angle-time curves for the powerlifting squat and box squat revealed participants selected one of two distinct techniques to perform the movement (Figures 8.3 and 8.4 illustrate representative curves for the distinct patterns used in the powerlifting squat). The first technique exhibited similar flexion and extension angles for the hip and knee as observed during the traditional squat (Figure 8.3). However, the movement also included substantially more rotation of the femur around the vertical and anterior-posterior axes than observed during the traditional squat. The second technique observed exhibited two distinct phases during the eccentric portion of the movement (Figure 8.4). Initially, movement was isolated in the sagittal plane at the hip joint. Upon reaching a critical hip flexion angle the knee and ankle simultaneously flexed along with concurrent abduction and internal rotation of the femur. Whilst the same overall movement patterns were observed for the powerlifting squat and box squat, the actual magnitude of torso inclination and ankle flexion during the eccentric phase were reduced when the box was introduced.

**Figure 8.2:** Representative joint angle-time curve for the traditional squat



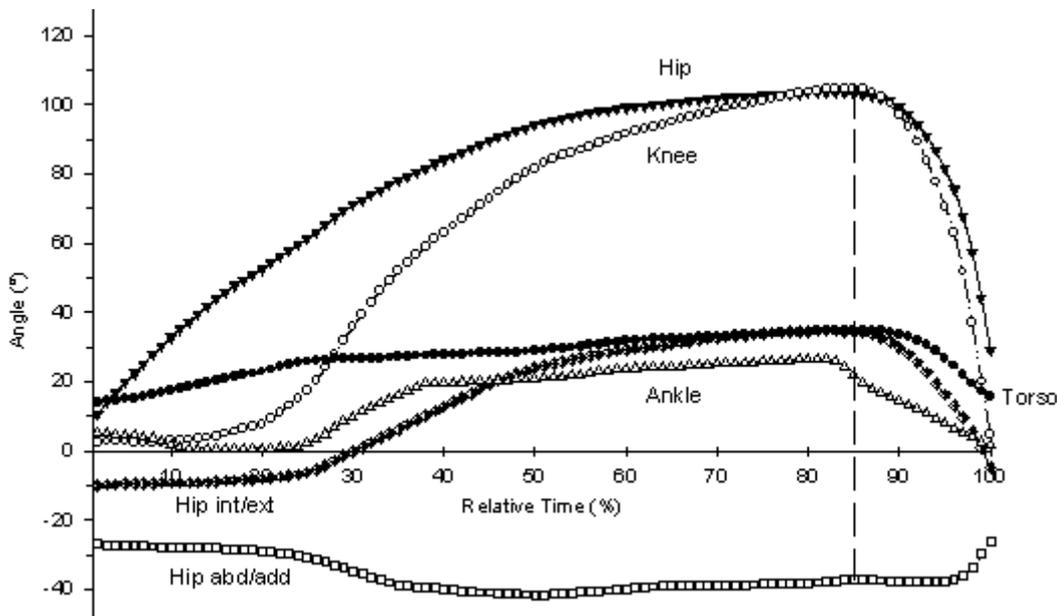
Dashed line indicates transition from eccentric to concentric

**Figure 8.3:** Representative joint angle-time curve for a distinct movement pattern observed during the powerlifting squat



Dashed line indicates transition from eccentric to concentric

**Figure 8.4:** Representative joint angle-time curve for a second distinct movement pattern observed during the powerlifting squat



Dashed line indicates transition from eccentric to concentric

### Angular Kinetics

Peak joint moments and moment arms are displayed in Table 8.3. Moment arms were calculated relative to the barbell centre and correspond with the time interval of the peak joint moment. Positive values indicate the barbell was anterior to the joint centre and negative values indicate a posterior barbell location. Significant differences were obtained for all joint moments and moment arms across the exercises. The greatest differences in peak joint moments were recorded at the spine and ankle. At both joints, the largest peak moments were produced during the traditional squat, followed by the powerlifting squat, then box squat. The addition of a box resulted in significant changes to a number of moment arms and peak joint moments. In particular, the use of a box decreased peak extension moments at the spine and hip and increased peak extension moments at the knee.

**Table 8.3:** Peak joint moments and corresponding moment arms (mean  $\pm$  SD)

|                     |                         | Traditional             | Powerlifting      | Box                |                  |
|---------------------|-------------------------|-------------------------|-------------------|--------------------|------------------|
| 30% 1RM             | <b>Moment arms (cm)</b> |                         |                   |                    |                  |
|                     | L5/S1                   | 23.5 $\pm$ 3.0†         | 22.9 $\pm$ 2.6‡   | 18.2 $\pm$ 2.3†‡   |                  |
|                     | Hip                     | 26.6 $\pm$ 2.7†         | 26.1 $\pm$ 2.1‡   | 21.1 $\pm$ 2.2†‡   |                  |
|                     | Knee                    | - 9.1 $\pm$ 1.8*†       | - 7.5 $\pm$ 1.2*‡ | - 13.9 $\pm$ 1.9†‡ |                  |
|                     | Ankle                   | 10.1 $\pm$ 2.0*†        | 5.3 $\pm$ 1.0*‡   | 2.5 $\pm$ 1.7†‡    |                  |
|                     | <b>Moments (Nm)</b>     |                         |                   |                    |                  |
|                     | L5/S1 (ext)             | 266 $\pm$ 36*†          | 222 $\pm$ 21*     | 203 $\pm$ 19†      |                  |
|                     | Hip (ext)               | 200 $\pm$ 26*           | 222 $\pm$ 29*‡    | 193 $\pm$ 28‡      |                  |
|                     | Hip (abd)               | 58 $\pm$ 18*            | 75 $\pm$ 25*      | 64 $\pm$ 28        |                  |
|                     | Hip (int rotation)      | 35 $\pm$ 16*            | 48 $\pm$ 18*‡     | 26 $\pm$ 10‡       |                  |
|                     | Knee (ext)              | 166 $\pm$ 28†           | 161 $\pm$ 24‡     | 197 $\pm$ 28†‡     |                  |
|                     | Ankle (ext)             | 82 $\pm$ 15*†           | 56 $\pm$ 8*‡      | 41 $\pm$ 11†‡      |                  |
|                     | 50% 1RM                 | <b>Moment arms (cm)</b> |                   |                    |                  |
|                     |                         | L5/S1                   | 22.6 $\pm$ 2.3†   | 21.9 $\pm$ 2.2‡    | 18.3 $\pm$ 2.6†‡ |
| Hip                 |                         | 25.9 $\pm$ 2.5†         | 25.8 $\pm$ 2.4‡   | 21.3 $\pm$ 2.8†‡   |                  |
| Knee                |                         | - 10.5 $\pm$ 1.9*†      | - 8.0 $\pm$ 1.4*‡ | - 14.7 $\pm$ 2.1†‡ |                  |
| Ankle               |                         | 9.5 $\pm$ 1.8*†         | 5.6 $\pm$ 1.5*    | 2.5 $\pm$ 2.1†     |                  |
| <b>Moments (Nm)</b> |                         |                         |                   |                    |                  |
| L5/S1 (ext)         |                         | 320 $\pm$ 42*†          | 261 $\pm$ 30*     | 233 $\pm$ 21†      |                  |
| Hip (ext)           |                         | 240 $\pm$ 29†           | 253 $\pm$ 33‡     | 213 $\pm$ 35†‡     |                  |
| Hip (abd)           |                         | 63 $\pm$ 29*            | 84 $\pm$ 27*      | 69 $\pm$ 35        |                  |
| Hip (int rotation)  |                         | 42 $\pm$ 24             | 50 $\pm$ 19‡      | 26 $\pm$ 17‡       |                  |
| Knee (ext)          |                         | 188 $\pm$ 32†           | 176 $\pm$ 27‡     | 221 $\pm$ 29†‡     |                  |
| Ankle (ext)         |                         | 93 $\pm$ 17*†           | 64 $\pm$ 16*      | 58 $\pm$ 15†       |                  |
| 70% 1RM             |                         | <b>Moment arms (cm)</b> |                   |                    |                  |
|                     |                         | L5/S1                   | 22.1 $\pm$ 2.5†   | 22.4 $\pm$ 2.3‡    | 19.7 $\pm$ 2.8†‡ |
|                     | Hip                     | 25.2 $\pm$ 2.9          | 26.2 $\pm$ 2.1‡   | 23.3 $\pm$ 3.0‡    |                  |
|                     | Knee                    | - 10.1 $\pm$ 1.1*†      | - 8.1 $\pm$ 0.8*‡ | - 15.2 $\pm$ 2.8†‡ |                  |
|                     | Ankle                   | 9.9 $\pm$ 2.2†          | 5.6 $\pm$ 1.6     | 2.4 $\pm$ 2.1†     |                  |
|                     | <b>Moments (Nm)</b>     |                         |                   |                    |                  |
|                     | L5/S1 (ext)             | 354 $\pm$ 49*†          | 308 $\pm$ 39*     | 279 $\pm$ 35†      |                  |
|                     | Hip (ext)               | 256 $\pm$ 35*†          | 281 $\pm$ 32*‡    | 230 $\pm$ 37†‡     |                  |
|                     | Hip (abd)               | 70 $\pm$ 30*            | 94 $\pm$ 26*      | 79 $\pm$ 35        |                  |
|                     | Hip (int rotation)      | 43 $\pm$ 24             | 55 $\pm$ 22       | 38 $\pm$ 28        |                  |
|                     | Knee (ext)              | 201 $\pm$ 39            | 192 $\pm$ 36      | 229 $\pm$ 39       |                  |
|                     | Ankle (ext)             | 104 $\pm$ 20*†          | 78 $\pm$ 10*      | 71 $\pm$ 14†       |                  |

\* Significant difference between traditional and powerlifting ( $p < 0.05$ )

† Significant difference between traditional and box ( $p < 0.05$ )

‡ Significant difference between powerlifting and box ( $p < 0.05$ )

Significant main effects of exercise type were also found for peak joint powers (Table 8.4). The largest differences were obtained at the Torso and ankle, where the greatest values were produced during the traditional squat. Significant main effects were also found at the hip where the largest peak joint power values were produced during the powerlifting squat.

**Table 8.4:** Peak joint powers (mean  $\pm$  SD)

|                |           | <b>Traditional</b> | <b>Powerlifting</b> | <b>Box</b>     |
|----------------|-----------|--------------------|---------------------|----------------|
| <b>30% 1RM</b> | Torso (W) | 238 $\pm$ 45†      | 203 $\pm$ 38        | 195 $\pm$ 28†  |
|                | Hip (W)   | 415 $\pm$ 61*†     | 450 $\pm$ 48*‡      | 347 $\pm$ 49†‡ |
|                | Knee (W)  | 408 $\pm$ 58†      | 410 $\pm$ 49‡       | 464 $\pm$ 41†‡ |
|                | Ankle (W) | 115 $\pm$ 28*†     | 83 $\pm$ 27*‡       | 54 $\pm$ 21†‡  |
| <b>50% 1RM</b> | Torso (W) | 211 $\pm$ 42†      | 185 $\pm$ 40‡       | 180 $\pm$ 23†‡ |
|                | Hip (W)   | 409 $\pm$ 64*      | 462 $\pm$ 50*‡      | 371 $\pm$ 47‡  |
|                | Knee (W)  | 416 $\pm$ 53       | 420 $\pm$ 48        | 450 $\pm$ 47   |
|                | Ankle (W) | 120 $\pm$ 30*†     | 76 $\pm$ 25*‡       | 58 $\pm$ 19†‡  |
| <b>70% 1RM</b> | Torso (W) | 180 $\pm$ 50†      | 174 $\pm$ 43‡       | 145 $\pm$ 24†‡ |
|                | Hip (W)   | 372 $\pm$ 61*      | 440 $\pm$ 47*‡      | 396 $\pm$ 41‡  |
|                | Knee (W)  | 409 $\pm$ 42       | 395 $\pm$ 40        | 400 $\pm$ 38   |
|                | Ankle (W) | 94 $\pm$ 21*†      | 64 $\pm$ 20*‡       | 48 $\pm$ 17†‡  |

\* Significant difference between traditional and powerlifting ( $p < 0.05$ )

† Significant difference between traditional and box ( $p < 0.05$ )

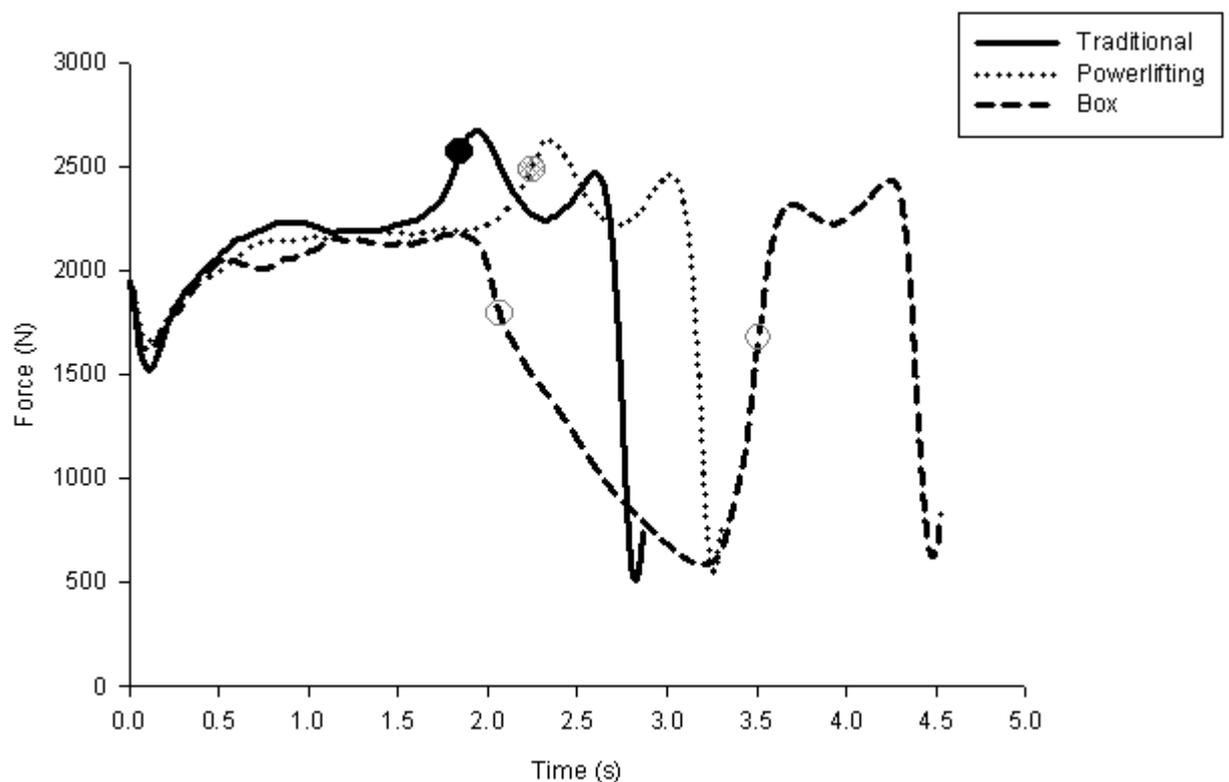
‡ Significant difference between powerlifting and box ( $p < 0.05$ )

### External Kinematics and Kinetics

The external stimulus of each exercise was assessed through measurement of the GRF, velocity, power and RFD. The vertical GRF maintained an overall similar profile for each exercise across loads. However, it was observed that as the external load increased the vertical GRF-time curve became more bimodal, with an increase in the relative size of the second peak. The group average vertical GRF-time curves performed with a load of 70% 1RM are displayed in Figure 8.5. The greatest differences in vertical GRF were observed during the box squat. There were no rapid increases in force production during the transition between eccentric and concentric phases as was evident with the other exercises. In

addition, as the individual sat and paused there was a gradual transfer of load from the system to the box resulting in a substantial reduction in force production. Across the loading conditions, significantly greater peak vertical GRF was obtained for the traditional squat and powerlifting squat compared to the box squat (Table 8.5). Significant differences were also obtained for peak velocity, peak power and RFD. The greatest differences were obtained for RFD where 3- to 4-fold larger values were obtained for the box squat.

**Figure 8.5:** Group average force time curves obtained with a 70% 1RM load



Circles indicate transition between phases of the squat (eccentric/concentric) and (eccentric/box/concentric)

**Table 8.5:** External kinematics and kinetics (mean  $\pm$  SD)

|                |                                   | <b>Traditional</b> | <b>Powerlifting</b> | <b>Box</b>         |
|----------------|-----------------------------------|--------------------|---------------------|--------------------|
| <b>30% 1RM</b> | Peak Force (N)                    | 2166 $\pm$ 194     | 2165 $\pm$ 182      | 2080 $\pm$ 280     |
|                | Peak Velocity (ms <sup>-1</sup> ) | 1.68 $\pm$ 0.15†   | 1.61 $\pm$ 0.19‡    | 1.44 $\pm$ 0.12†‡  |
|                | Peak Power (W)                    | 2901 $\pm$ 293†    | 2825 $\pm$ 315‡     | 2472 $\pm$ 288†‡   |
|                | RFD (Ns <sup>-1</sup> )           | 4801 $\pm$ 1572†   | 4963 $\pm$ 1542‡    | 16390 $\pm$ 4204†‡ |
| <b>50% 1RM</b> | Peak Force (N)                    | 2448 $\pm$ 295†    | 2400 $\pm$ 270‡     | 2265 $\pm$ 306†‡   |
|                | Peak Velocity (ms <sup>-1</sup> ) | 1.39 $\pm$ 0.14    | 1.34 $\pm$ 0.13     | 1.31 $\pm$ 0.11    |
|                | Peak Power (W)                    | 2702 $\pm$ 114     | 2695 $\pm$ 161      | 2589 $\pm$ 307     |
|                | RFD (Ns <sup>-1</sup> )           | 5319 $\pm$ 1334†   | 5333 $\pm$ 1443‡    | 16980 $\pm$ 3199†‡ |
| <b>70% 1RM</b> | Peak Force (N)                    | 2680 $\pm$ 309†    | 2685 $\pm$ 301‡     | 2528 $\pm$ 302†‡   |
|                | Peak Velocity (ms <sup>-1</sup> ) | 1.18 $\pm$ 0.16    | 1.16 $\pm$ 0.12     | 1.12 $\pm$ 0.09    |
|                | Peak Power (W)                    | 2637 $\pm$ 137     | 2589 $\pm$ 135      | 2484 $\pm$ 301     |
|                | RFD (Ns <sup>-1</sup> )           | 5083 $\pm$ 1227†   | 5868 $\pm$ 1972‡    | 14537 $\pm$ 3612†‡ |

\* Significant difference between traditional and powerlifting ( $p < 0.05$ )

† Significant difference between traditional and box ( $p < 0.05$ )

‡ Significant difference between powerlifting and box ( $p < 0.05$ )

## 8.5 Discussion

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The results of the present study reveal significant biomechanical differences between three popular movement strategies used to perform the squat exercise. One of the most significant technical differences noted was the stance width used for each technique. All of the athletes in the present study self-selected a narrow stance when performing the traditional squat and a wide stance when focusing on restricting anterior displacement of the knee during the powerlifting squat box squat. Previous research investigating the effects of stance width on squatting biomechanics has reported a number of findings similar to those obtained here (Escamilla et al. 2001a). Using video data collected during a powerlifting competition, Escamilla et al. (2001a) reported that athletes performing wide stance squats exhibited greater hip flexion and smaller plantarflexion angles than those performing narrow stance squats. These results correspond with the significant differences in joint angles recorded in the present study between the narrow stance traditional squat and the wide stance powerlifting squat. In addition, Escamilla et al. (2001a) reported similar effects of stance width on hip and ankle moments. In particular, wide stance squats were found to produce significantly larger hip extension moments and smaller ankle extension moments. In contrast to the findings of the present study, Escamilla et al. (2001a) reported that overall joint-time curves for the torso and lower body were similar between narrow and wide stance squats. However, data collected by Escamilla et al. (2001a) were recorded during an active competition and the authors were unable to influence the lifting techniques employed; whereas, in the present study athletes were instructed to let the knee travel past the toes during the traditional squat and to maximise posterior displacement of the hip during the powerlifting squat and box squat. These instructions resulted in different movement strategies beyond alterations to stance width. The joint-time curves for the traditional (narrow stance) squat were consistent across participants and featured simultaneous flexion then extension of the hip and knee, with greater range of motion obtained at the knee joint (Figure 8.2). During the powerlifting squat and box squat (wide stance) two distinct techniques were observed. The first technique also featured simultaneous flexion then extension of the hip and knee. However, the movement was combined with significantly greater ab/adduction and int/external rotation of the femur compared to that measured during the traditional squat (Figure 8.3). The second technique observed during wide stance squats featured two distinct phases during the eccentric portion of the movement (Figure 8.4). The first phase consisted of isolated hip flexion to approximately 40 degrees. Upon reaching this point, the second phase of the movement was initiated and comprised rapid flexion of the knee and ankle, combined with substantial abduction and

internal rotation of the femur. The different movement strategies selected were clearly influenced by the stance width adopted. When attempting to displace the knees past the toes a narrow stance may have been selected to facilitate tracking of the patella over large knee flexion angles. In contrast, a wide stance was most likely adopted when attempting to maximise posterior displacement of the hip in order to decrease the height of the system COM and increase overall stability.

When discussing the advantages and potential risks associated with each type of squat, researchers and practitioners have generally focused on the kinetics associated with the exercise (Chiu, Heiler and Sorenson 2009). Based largely on research conducted by Fry et al. (2003) it is commonly believed that squats that minimise anterior displacement of the knee produce greater muscular forces at the hip and require a more horizontal torso position to remain balanced. Importantly, it is suggested that this torso position creates larger forces and moments at the lumbar spine, thereby increasing the risk of developing lower back injuries (Fry, Smith and Schilling 2003). The results from the present study support claims that greater muscular forces are generated at the hip when attempting to maintain a more vertical shin position. This conclusion is based on significant differences in peak joint moments measured between the traditional squat and powerlifting squat. In contrast to the findings of Fry et al. (2003), the results obtained here demonstrate that positioning of the torso is not dependent on the amount of anterior knee displacement. In addition, the largest peak moments at the L5/S1 joint in the present study were measured during performance of the traditional squat and not the powerlifting squat as would have previously been expected. Collectively, the results contradict previous suggestions that there is a greater risk of developing lower back injuries when performing variations such as the powerlifting squat. Contrasting results may be due to a number of methodological differences between the studies. Participants recruited by Fry et al. (2003) were recreationally trained and attempted to adopt similar movement strategies when performing the traditional squatting technique and the variation with restricted anterior knee displacement. Conversely, participants in the present study were competitive powerlifters with sufficient experience in both exercises to select different movement strategies. Based on consistent technical features adopted by all athletes in the present study, it is clear that maintaining a relatively upright torso position whilst restricting anterior displacement of the knee is best achieved by adopting a wide stance and achieving significant range of motion at the hip joint in all three planes of motion. This may have implications for individuals who choose to perform the powerlifting squat or restrict anterior displacement of the knee but have limited movement capabilities at the hip joint.

Differences in peak joint torques recorded for each exercise were largely a result of the relative displacements of the barbell and joint centres. Performance of the traditional squat created relatively large anterior displacements of the barbell, knee and system COM during the eccentric phase (Table 8.1). In contrast, use of the box enabled individuals to maximise posterior displacement of the hip which resulted in an overall posterior displacement of the barbell. Visual observation of box squat repetitions revealed that many of the powerlifters displaced the system COM behind the base of support during the final stages of the eccentric movement. The use of the box to safely maximise posterior displacement created an ordered succession of squatting motions with the traditional squat situated at one end of the spectrum and the box squat at the other. A number of peak joint moments analysed in the present study reflected this ordered succession. At the ankle joint, peak extension moments were greatest during the traditional squat, followed by the powerlifting squat, then box squat. These differences would have been caused by variation in displacement of the system COM. Greater anterior displacements created during the traditional squat would require increased joint moments to compensate for the greater total resistance (Wretenberg, Feng and Arborelius 1996). Based on the results of previous research (Fry, Smith and Schilling 2003, Wretenberg, Feng and Arborelius 1996) and large differences noted across techniques for anterior knee displacement, a similar ordered effect was expected for peak moments developed at the knee joint. However, the results showed that the largest peak moments were obtained during the box squat, with similar smaller values obtained during the traditional squat and powerlifting squat. For each exercise the peak knee extension moment was developed during the initial stage of the concentric movement. As individuals maintained a more upright torso position when performing the box squat, the greater resistance moment arm created explains the larger peak moment recorded. The magnitude of the resistance moment arm created at the knee joint was similar between the traditional squat and powerlifting squat. As a result, no significant difference was measured between the two exercises. This result contradicts findings from previous research reporting reduced knee moments when maintaining a more vertical shin position (Fry, Smith and Schilling 2003). However, previous results were associated with an increased forward lean of the torso which did not occur in the present study. It is also important to note, that the overall mechanical stress experienced at the knee may not be adequately described by the peak moment alone. Evidence has shown that compressive and shear forces at the knee increase with larger flexion angles and greater displacement of the femur relative to the tibia (Schoenfeld 2010, Escamilla et al. 2001b, Wretenberg, Feng and Arborelius 1996). As a result, it is expected that greater overall stress at the knee joint will occur during the traditional squat.

Significant kinetic differences were also obtained at the hip joint. Across exercises, the largest peak moment was obtained during performance of the powerlifting squat. This result may be due to a number of biomechanical and physiological factors. The increased forward lean of the torso during the powerlifting squat in comparison to the box squat would have created a larger resistance moment arm at the hip, which would explain the difference in peak extension moment found. However, a significant difference was also obtained between the powerlifting squat and traditional squat despite both exercises creating similar resistance moment arms. The difference may have been caused by variation in recruitment of the muscles surrounding the hip joint. Researchers have previously commented that powerlifters intentionally emphasise hip extension when performing wide stance squats (Wretenberg, Feng and Arborelius 1996). Support for this claim can be found in multiple studies which have reported increased muscle activity of the gluteus maximus when squats are performed with wider stance widths (McCaw and Melrose 1999, Paoli, Marcolin and Petrone 2009). In addition to creating the largest extension moment at the hip, the powerlifting squat also produced the largest peak abduction and peak axial rotation moments. These larger kinetic values correspond with greater frontal and transverse rotations of the femur during the powerlifting squat compared to the other exercises.

Recently, there has been interest in altering the position of the femur during squatting exercises to target specific muscle groups (Escamilla et al. 2001b, Pereira et al. 2010, Signorlie et al. 1995). Anecdotally, it is believed that performing the squat with the hip in external rotation increases muscle activity of the quadriceps and hip abductors (Signorlie et al. 1995). Research conducted thus far has failed to demonstrate changes in quadriceps activity with altered rotation of the femur (Escamilla et al. 2001b, Signorlie et al. 1995); however, data exists to suggest that muscle activity of the hip abductors can be influenced (Pereira et al. 2010). Previous studies have attempted to control the position of the femur by fixing the orientation of the foot. However, during the present study significant axial rotation was measured despite the foot remaining still. For each exercise the movement was initiated with the foot abducted and the hip externally rotated. As the movement progressed, foot position remained fixed as the hip moved in and then out of internal rotation. Results from other kinematic studies incorporating 3D motion capture systems have reported similar results for athletes performing the squat (Decker, Krong, et al. 2009, Wu, Lee, et al. 2011). This observation may have implications for potential injuries at the knee joint as evidence has shown that hip adduction combined with internal rotation of the femur during knee flexion exercises is associated with increased valgus stress and repetitive injuries such as anterior cruciate ligament strain, iliotibial band friction syndrome and patellofemoral pain

syndrome (Ireland 2002, Leetun et al. 2004). During the bottom portion of the squat where internal rotation of the femur was at its greatest, the athletes in the present study were able to maintain appropriate alignment of the femur and tibia through substantial abduction of the hip. During the powerlifting squat where internal rotation and hip flexion is maximised, untrained individuals and those with restricted movement capabilities may be unable to maintain hip abduction. This may lead to those individuals descending into an adducted and internally rotated posture which could create inappropriately large stresses at the knee.

In order to obtain a more complete understanding of the biomechanical stimulus presented by an exercise, recent research has focused on the external kinematics and kinetics created (Cormie et al. 2007, Zink et al. 2006, Kawamori et al. 2006). Most frequently, variables such as force, velocity, power and RFD have been measured (American College of Sports Medicine 2009). The data obtained have also been used to rank exercises based on the belief that those which acutely maximise the production of each variable provide the best stimulus for longitudinal improvement. To ensure the biomechanical stimulus is maximised for each variable, repetitions in the present and previous studies were performed with the intention to lift the load as fast as possible (Cormie et al. 2007, Zink et al. 2006, Kawamori et al. 2006). The results obtained here demonstrate that large forces can be produced in all three squatting exercises even when light resistances are displaced with maximum velocity. Across the 30 to 70% 1RM loads, peak vertical GRF for the group was approximately 2.1 to 2.8 times body weight. The largest effects of squat variation on force and all other external kinematics and kinetics recorded were obtained during the box squat. Group average force-time curves showed reduced peak values and changes to the overall profile with the box squat compared to the other exercises (Figure 8.5). During the traditional squat and powerlifting squat a large increase in force was measured during the transition period between eccentric and concentric phases. However, during the box squat, athletes were able to decrease force production during this transition period and use the box to partially slow the movement of the system COM. Following a sustained reduction in force as the athletes paused on the box, force was then rapidly increased during the concentric phase. A similar reduction in peak force when performing the box squat was reported in a recent study conducted by McBride et al. (2010); the authors suggested that lower forces produced during the box squat compared to a standard squatting movement was the result of reduced stretch-shortening activity from pausing on the box. The powerlifters in the present study were instructed to follow their individual practices regarding the length of time paused on the box, as long as a minimum period of one second was adhered to. On average, the group paused for 1.7 seconds with times ranging from 1.3 to 2.3 seconds. Research has

shown that as duration between eccentric and concentric phases increases, there is a progressive reduction in contribution from the stretch shortening cycle (Wilson, Murphy and Pryor 1994). The long pauses obtained during the box squat are therefore likely to explain the reduced force production in comparison to the other exercises studied.

The largest effect of squat variation observed on external variables was an increase in RFD measured during the box squat. The results showed 3 to 4-fold greater values in RFD when squats were performed with the box. As RFD and the squat exercise are both considered important elements of training for athletic improvement (Cronin and Sleivert 2005), the finding that significantly greater values can be obtained when using the box could have important implications for training prescription. Whilst it remains unclear which training practices are most effective for long-term improvements in RFD, many believe that performing explosive resistance exercises that create high values in the variable will be successful (Cronin and Sleivert 2005). The large disparity in values obtained between the exercises may provide researchers with an effective model to study RFD using movements that are transferable to many sporting actions.

Internal and external peak power values followed a similar pattern across loads. Maximum values were generally produced at 30 or 50% 1RM with relatively small decreases in magnitude obtained at 70% 1RM. Across loads the largest external power values were produced during the traditional and powerlifting squat, with significantly lower values produced during the box squat. It is also likely that the reduced power values created during this exercise are the result of differences in expression of the SSC phenomenon. Measurement of internal power values provided additional information by recording values at the different joints. The greatest differences between exercises were found at the torso and ankle where the largest joint power values were produced for the traditional squat, followed by the powerlifting squat then box squat. Significant main effects were also obtained at the hip, where the larger peak moments and displacements measured during the powerlifting squat also resulted in the highest joint power values. For each of the squatting movements the majority of the total power produced was developed at the hip and knee. This finding may assist practitioners who aim to improve performance of explosive sporting movements that feature a similar distribution pattern.

## 8.6 Summary and Conclusion

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The present study investigated the practice of altering the movement strategy of an exercise to change the associated biomechanical stimulus. In the contemporary training of powerlifters this practice is combined most frequently with the squat. The investigation demonstrated that the movement strategy used to perform the squat could be altered through the constraint of maintaining as vertical a shin position as possible. The results confirmed that changes to the movement strategy had a significant effect on a range of kinematic and kinetic variables. In particular, the altered techniques resulted in substantial kinematic and kinetic changes at the hip and reduced kinetic output at the ankle.

The investigation also demonstrated that the movement strategy and associated biomechanical stimulus could be altered further by performing the box squat. Incorporating the additional apparatus enabled participants to maximise posterior displacement of the hip whilst maintaining an upright torso position. This posture resulted in significant kinetic changes at all joint measured. External kinematics and kinetics were also affected when performing the box squat. Decreases in force, power and velocity were measured and most likely caused by attenuation of the SSC action when pausing on the box. However, the altered movement strategy also resulted in 3 to 4-fold greater RFD values. This final result suggests that the box squat could be an effective exercise for athletes to develop their ability to produce large amounts of force over relatively short time periods.

## CHAPTER 9. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

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### 9.1 Summary

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This PhD summarises the work from the initial stages of a proposed larger research project to determine the effectiveness of contemporary powerlifting training practices for general athletes. The specific aims of this PhD were, firstly, to identify the contemporary training practices used by powerlifters and secondly, to provide a detailed analysis of the biomechanical stimulus created. In addition, a third aim of the PhD was to assess whether the training practices investigated could provide appropriate mechanical stimuli for athletes of other sports. The aims of the PhD have been achieved through the implementation of five separate, though related studies as part of a research design that progressed from descriptive to experimental work.

The contemporary training practices of powerlifters were identified in study one through use of questionnaires and semi-structured interviews. The sample comprised many of the United Kingdom's top male powerlifters competing at that time. The study revealed that the participants training practices were heavily influenced by information disseminated through online sources. Analysis of the lay literature and the interviews conducted revealed that each of the contemporary training practices adopted by powerlifters was associated with a proposed mechanism that explained how the practice might improve performance. Many of the proposed mechanisms were biomechanical in nature, and therefore, correspond well with the aims and design of this PhD. The training practices that were identified in the study were categorised based on their underlying mechanical premise. A total of four categories were considered, including: (1) Speed of movement; (2) Alterations to the external resistance; (3) Movement strategy; and (4) Use of ergogenic equipment. Only the first three categories were considered to comprise training practices that had the potential to improve the performance of athletes other than powerlifters, and therefore only these categories were investigated further.

The aim of assessing whether the training practices identified could provide appropriate mechanical stimuli for general athletes was first addressed by investigating the variables that influenced performance of common sporting tasks. A regression based approach was adopted to obtain predictor models that combined multiple variables. Based on the suggestions of previous researchers (Cronin and Sleivert 2005), anthropometric and biomechanical variables were included in the analyses. However, the best one-, two- and three-factor predictor models included biomechanical variables only. The results demonstrated that maximum strength expressed relative to body mass is the basic quality that determines an athlete's ability to perform common sporting tasks such as sprinting, jumping and changing direction. The explanatory power of the models was increased by combining the athletes' relative strength scores with their ability to produce high velocity, power and RFD values. The results also suggested that there may be an element of specificity with different mechanical variables appearing more prominently in models for particular sporting tasks. The adjusted coefficients of determination for the best three factor model ranged from 0.43 to 0.86 across the different sporting tasks. These results demonstrated that force, velocity, power and RFD variables explain a substantial amount of the variation in performance of common sporting movements, and therefore provide suitable measures to assess the mechanical stimuli created with the novel training practices.

To provide a detailed analysis of the biomechanical stimulus associated with the training practices, internal variables (including joint angles, velocities, moments and powers) as well as external variables required calculation. A rigid segment model comprising the foot, shank, thigh, pelvis and thorax was used to calculate the internal variables. Evaluation of the model revealed that similar designs have been tested extensively with resistance training movements and demonstrated robustness to small errors in inputs. Importantly, the model provided an appropriate balance between complexity and validity of inherent assumptions.

The first experimental study investigated the training practice of performing traditional resistance exercises with the intent to lift the load as fast as possible. The deadlift exercise was selected for analysis due to its popularity amongst powerlifters and the rapid extension it requires in the lower body joints, which is characteristic of many sporting movements. In addition, aspects of the deadlifts gross movement pattern was considered to be similar to the power clean, which is regarded as one of the most effective exercises for developing power and was used as a model comparator for the study. The deadlift was performed at

sub-maximum and maximum velocity across a range of external loads. The results showed that performing the movement with the intent to lift the load as fast as possible significantly increased the expression of almost all internal and external kinematic and kinetic variables measured, thereby demonstrating a more effective mechanical stimulus to induce adaptations. Comparisons of the deadlift with the power clean revealed that the mechanical stimulus associated with each exercise was more similar than previously would have been considered. Significantly greater external force values were obtained with the deadlift, whereas, significantly greater velocity, power and RFD values were obtained with the power clean. However, the internal variables revealed similar maximum joint velocity and joint power values for both exercises across the loads, with larger net joint moments generally obtained with the deadlift.

The second experimental study investigated the effects of manipulating the external resistance. The study investigated two of contemporary powerlifters' most popular and visually recognisable training practices, namely, the use of variable resistance material and unconventional barbells. Chain resistance was selected to investigate the effects of variable resistance, and the hexagonal barbell selected to investigate potential changes when altering the position of the external load. The deadlift was performed with both practices to expand on the work from the previous study. Resistance trained athletes experienced in using chain resistance performed repetitions with weight plates only and with a combination of weight plates and chains. The magnitude of the chain resistance included was substantially greater than that used in previous studies, but reflected the loads used by high-level powerlifters. The results showed that the inclusion of chains had a significant effect on all external kinematic and kinetic variables calculated. Temporal analysis of the VGRF data demonstrated that the inclusion of chains enabled significantly greater forces to be maintained at the final stages of the movement. This result confirmed the hypothesis of powerlifters and other proponents of this training practice. However, the results also revealed that the addition of chain resistance resulted in significant decreases in velocity and power, with greater effects obtained when using heavier barbell and chain loads. This result contradicted the perceptions of the athletes in the study and those that promote the practice. At present it is not clear why there is such a large discrepancy between the actual and perceived outcomes when using chain resistance.

A large number of mechanical changes were also obtained when using the hexagonal barbell. Comparisons of the deadlift performed with the straight or hexagonal barbell revealed that the irregular shape enabled athletes to produce significantly greater force,

velocity, power and RFD values. The rigid body models revealed that deadlifts performed with the hexagonal barbell produced significantly greater net joint moments at the knee, whilst significantly reducing the net joint moments experienced at the hip and lumbar spine. Differences in production of internal and external kinematic and kinetic variables could be explained by changes in positioning of the external resistance and the subsequent resistance moment arms created. Importantly, the results expand on those obtained from the first experimental study and demonstrate that the biomechanical stimulus created with the contemporary training practices may be further enhanced by combining practices.

The final experimental study investigated the effects of altering the movement strategy used to perform the squat. This was achieved by instructing the participants to maximise the posterior displacement of the hip and to maintain as vertical a shin position as possible. In the literature, this movement strategy describes the powerlifting squat. The participants also followed the same instructions whilst performing the squat onto a box (also referred to as the box squat). In agreement with observations from the lay material, the powerlifters in the study met the constraints by adopting a wide stance and creating relatively large ranges of motion at the hip joint in the frontal and transverse planes. In addition, two distinct movement patterns were observed based on the relative timing of the hip and knee during the descent. The results showed that force, velocity, power and RFD values were relatively unaffected by performing the powerlifting squat in comparison to a traditional squatting motion; whereas, the disruption between the eccentric and concentric phases of the motion when pausing on the box significantly decreased force, velocity and power, whilst significantly increasing RFD. Despite minimal differences in external variables measured between the traditional and powerlifting squat, a number of significant differences in the internal variables were found, including the joint moments and powers produced at the spine, hip and ankle. Analysis of internal variables produced during the box squat revealed that, in direct contrast to the available anecdotal information relating to this exercise, the movement results in decreased moments at the spine and increased moments at the knee compared with other squatting movements.

## 9.2 Conclusions

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The work reported in this thesis has expanded the existing knowledge of the contemporary training practices of powerlifters and their potential benefit for general athletes. Specifically, the results have shown that a collection of the most popular practices have the potential to substantially alter and enhance the biomechanical stimulus of more traditional training regimes. In presenting these novel findings, the work provides clear initial support for the use of these contemporary practices with general athletes. The findings from each of the experimental studies plus additional related work have been disseminated in peer reviewed journals closely aligned with the discipline of strength and conditioning. The impact of this work has already influenced discussions amongst practitioners regarding the most effective training methods to enhance the athletic potential of individuals competing in sports that require the development of large force and power outputs, thereby fulfilling one of the major goals of applied research. Importantly, the thesis as a whole provides a framework with which to interpret and apply the novel results within current paradigms used in strength and condition.

Additionally, this work has highlighted the importance of collecting empirical data when assessing the stimulus created by a training practice. Many of the biomechanical effects obtained correspond with the anecdotal information disseminated by athletes that regularly performed the practices. However, some important results (e.g. the negative effects of chain resistance on velocity and power, and the distribution of net joint moments during box squats) characterising the biomechanical stimulus were contrary to that promoted by athletes and coaches, reinforcing the importance of scientific study.

As each of the training practices investigated in the study demonstrated the potential to alter the biomechanical stimulus of a resistance exercise, there are opportunities to enhance training adaptations with each practice depending upon the particular goals. The following practical applications are made based upon the data collected:

- Athletes seeking to develop muscular power should perform resistance exercises with the intent to lift the load as fast as possible. In contrast to statements made by

other researchers in strength in conditioning, this work supports the use of performing traditional resistance exercises, such as the deadlift, explosively as a means to directly enhance power. However, it is noted that there may be other exercises such as jump squats and Olympic weightlifting movements that provide a more effective stimulus and may be selected preferentially, particularly when only a limited number of exercises are to be selected.

- The biomechanical effects of including variable resistance in the form of either bands or chains are likely to be distinct. Due to reductions in acute expression of velocity and power, it is recommended that training with heavy chain loads (i.e.  $\geq 20$  1RM) be used primarily to develop maximum strength.
- When using the deadlift to increase strength or power, the exercise should generally be performed with the hexagonal barbell to maximise the biomechanical stimulus. For variation, or to specifically target the lumbar erectors, the straight barbell deadlift may be a more effective option. The redistribution of muscular effort when performing the deadlift with the hexagonal barbell also suggests that the exercise could be used as an appropriate variation for the squat.
- The back squat should be considered as existing on a spectrum with the close stance traditional movement at one end and the wide stance powerlifting-style movement at the other. When the goal is to evenly distribute the muscular effort throughout the segments of the body, a movement pattern close to the traditional movement should be selected. However, if the goal is to target the musculature of the hip or reduce stress at the ankle, the powerlifting-style movement should be selected.
- For those athletes seeking to develop proficiency in the powerlifting-style movement, the box squat should be incorporated as part of their skill acquisition training. In addition, the box squat may provide an appropriate means for athletes to enhance their ability to produce high RFD values.

### **9.2.1 Limitations**

It is important to be aware of the following limitations when interpreting and applying the results from this thesis:

- Whilst the powerlifters surveyed and interviewed were of an elite level, the sample size was relatively small and therefore may not accurately represent the training practices of other groups of powerlifters. Importantly, the training practices identified in the study should not be considered as an exhaustive list of those currently used.
- The biomechanical variables selected to model performance in common sporting tasks (and subsequently used to assess the biomechanical stimulus of the contemporary training practices) represent a small sample of those which are potentially applicable.
- Only single sets and repetitions were performed at each load in the experimental studies. Modelling more realistic training sessions would have introduced variability in sets, repetitions and recovery intervals creating substantial complexity and the need for far larger and unrealistic numbers of participants. As a result, the kinematic and kinetic findings of this study may differ from that produced in standard sessions comprising multiple sets and repetitions.

### **9.3 Recommendations for future work**

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As discussed in the introduction to this thesis, the scientific investigation of any training practice requires extensive study employing a wide range of methodological approaches. The aim of this type of applied research is to create a robust evidence base that can be used to positively impact sporting performance of athletes. To develop the research on the practices investigated here and potentially influence practice, a logical progression of study must be pursued. The structure of the PhD corresponds with the initial research stages proposed by Bishop in his 'applied research model for the sport sciences' (Bishop 2008). The recommendations for future work on this topic closely follow the progression outlined in the same model.

It is recommended that the next stage of the research process include longitudinal interventions to assess whether the practices studied have a substantial effect on physical performance, and markers of sporting performance. Studies should be characterised by the tight control of variables with well trained participants included to maximise external validity. Overall quality of studies could be enhanced by including cross-over designs with control and comparison groups. Similar methodologies to those used in this PhD to collect external mechanical variables should also feature in longitudinal designs to more effectively characterise the mechanical stimulus and determine whether changes occur with adaptations. Importantly, physiological variables can also be assessed to analyse the metabolic and hormonal stimulus produced, and identify the site of adaptations (i.e. neural, muscle architecture, myocellular).

If the longitudinal investigations demonstrate that the training practices can be used effectively to enhance physical and sporting performance, then the final stages of the research model should be completed. Bishop (2008) recommends that potential barriers (and motivators) to uptake should be explored at this stage of the process. It is argued that an understanding of the issues coaches must deal with (e.g. injuries, concurrent training, lack of equipment, expertise) and the infrastructure required to achieve implementation must be gained (Bishop 2008). Research in this area has not been published in the sport science literature, but could be useful in creating uptake in novel training practices. In addition, findings from this stage of the process may lead to refinements of the training practices or scope of research conducted in previous stages of the model. For example, coaches may wish to know if the training practices are suitable for athletes to perform during competition periods where the overall physical load is high. To resolve the issue, intervention studies may be repeated with similar athletes or trained populations with concurrent training to simulate the required environment.

The final stage of the research process should attempt to gain evidence that the training practices can be implemented with high level athletes and are as effective (if not more so) than current practices. It may be appropriate at this stage of the process to transition from group based studies to idiographic research featuring single-subject designs to facilitate understanding of the real-world effects. The advantages of this approach is that each participant acts as their own control, information can be obtained over lengthy time periods (which are required for elite athletes to display improvements), and it avoids ethical issues such as certain athletes receiving the control condition. To effectively study the training

practices investigated here, multiple introduction and removal phases of a practice would be required, with periods allocated to the combination of practices. These intervention phases would be preceded by a relatively length baseline period to establish the inherent variability of the athletes' performance.

Due to the complex nature of research and the advancement of training practices it is not envisaged that the research model presented will flow linearly from start to finish. Rather, a bidirectional process is likely to occur with findings obtained from distinct sections influencing each other. In the process of completing this PhD several areas of interest which may influence the earlier stages of the research process have arisen, these include:

- Consideration of further refinement to contemporary training practices identified – for example, use of the double knee bend technique when performing the deadlift, identification of best simultaneous combinations of bands and chains, technology to provide immediate feedback regarding production of important biomechanical variables, use of smart fabrics to create ergogenic clothing with greater crossover to general athletes.
- Consideration of applicability to females, whose relevant anatomical and biomechanical parameters may differ from males.
- Consideration of the most effective methods to develop proficiency with the various training practices.

## APPENDICES

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### Appendix I: Study One Questionnaire

Personal information and results will be kept confidential and anonymous. The purpose of this information is solely to produce an academic report detailing the training practices of top level powerlifters.

NAME: .....

DATE OF BIRTH: .....

WEIGHT CLASS: .....

Email: .....

1) Once warmed up do you perform your **squat** repetitions:

As fast as possible  
(maximum)

At speeds less than  
maximum

Mixture of maximum  
& less than maximum

2) Once warmed up do you perform your **bench press** repetitions:

As fast as possible  
(maximum)

At speeds less than  
maximum

Mixture of maximum  
& less than maximum

3) Once warmed up do you perform your **deadlift** repetitions:

As fast as possible  
(maximum)

At speeds less than  
maximum

Mixture of maximum  
& less than maximum

4) During your training do you ever perform the **squat** at maximum speed with weights at or lower than 70% of your maximum (1RM)? I.e. “**speed squats.**”

Yes

No

5) If you answered yes to question 4, what loads (as a % of your maximum) do you use to perform your **speed squats**? (Please select more than one if appropriate.)

0-10%

10-20%

20-30%

30-40%

40-50%

50-60%

60-70%

6) During your training do you ever perform the **bench press** at maximum speed with weights at or lower than 70% of your maximum (1RM)? I.e. “**speed bench press.**”

Yes

No

7) If you answered yes to question 6, what loads (as a % of your maximum) do you use to perform your **speed bench presses**? (Please select more than one if appropriate.)

0-10%

10-20%

20-30%

30-40%

40-50%

50-60%

60-70%

8) During your training do you ever perform the **deadlift** at maximum speed with weights at or lower than 70% of your maximum (1RM)? I.e. “**speed deadlift.**”

Yes

No

9) If you answered yes to question 8, what loads (as a % of your maximum) do you use to perform your **speed deadlifts**? (Please select more than one if appropriate.)

- 0-10%     10-20%     20-30%     30-40%     40-50%     50-60%     60-70%

10) Do you ever include lower body plyometric drills (i.e. explosive jumping) as part of your power lifting training?

- Yes     No

11) Do you ever include upper body plyometric drills (i.e. rebound medicine ball throws) as part of your power lifting training?

- Yes     No

12) Do you ever include Olympic weight training lifts as part of your power lifting training? (Please select more than one if appropriate.)

- No     Yes the Clean     Yes the Snatch     Yes the Jerk     Yes the high Pull

13) Do you ever include elastic bands as part of your powerlifting training? (Please select more than one if appropriate.)

- No     Yes for the Squat     Yes for the Bench Press     Yes for the Deadlift     Yes for Assistance Exercises

14) Do you ever include chains as part of your powerlifting training? (Please select more than one if appropriate.)

|                       |                       |                       |                       |                       |
|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| No                    | Yes for the           | Yes for the           | Yes for the           | Yes for               |
|                       | Squat                 | Bench Press           | Deadlift              | Assistance Exercises  |
| <input type="radio"/> |

15) Do you perform box squats as part of your powerlifting training?

|                       |                       |                       |                       |
|-----------------------|-----------------------|-----------------------|-----------------------|
| No                    | Yes, less than        | Yes, the same as      | Yes, more than        |
|                       | Free Squats           | Free Squats           | Free Squats           |
| <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> |

16) Do you ever use "boards" when bench pressing as part of your powerlifting training?

|                       |                       |
|-----------------------|-----------------------|
| Yes                   | No                    |
| <input type="radio"/> | <input type="radio"/> |

17) Do you use some form of periodization in your organizing powerlifting training?

|                       |                       |
|-----------------------|-----------------------|
| Yes                   | No                    |
| <input type="radio"/> | <input type="radio"/> |

18) What assistance exercise do you believe best improves your **squat**?

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19) What assistance exercise do you believe best improves your **bench press**?

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20) What assistance exercise do you believe best improves your **deadlift**?

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Please sign here to acknowledge that you have granted permission for your results to be included in an academic report.

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Thank you for your assistance

## Appendix II: Study One Semi-Structured Interview Schedule



**ROBERT GORDON  
UNIVERSITY • ABERDEEN**

**Question 1:** Can you tell me a little bit about your background in powerlifting?

**Question 2:** Do you think information on powerlifting training has changed recently?

**Question 3:** Do you think the training practices of powerlifters have changed recently?

**Question 4:** How would you describe your training practices?

**Question 5:** Do your training practices change the closer you get to competitions?

**Question 6:** Are there any training practices you perform that you think may be quite unique?

**Question 7:** Are there any training practices incorporated by other powerlifters that you don't agree with?

**Question 8:** How do you structure your powerlifting training?

**Question 9:** How do you progress your powerlifting training?

### **Appendix III: Derivation of equations of motion for the barbell, barbell + bands and barbell + chains, based on the work-energy principle**

#### **Barbell:**

The work done on the barbell is equal to the sum of the change in potential energy and change in kinetic energy of the barbell respectively:

$$F dz = mg dz + d \left( \frac{1}{2} m \dot{z}^2 \right). \quad (1)$$

Where  $F$  is the force applied,  $dz$  is the infinitesimal displacement in the vertical direction,  $m$  is the mass,  $g$  is the acceleration due to gravity,  $z$  is the vertical position and a dot over the symbol indicates time differentiation (thus  $\dot{z}$  is the vertical velocity and  $\ddot{z}$  is the vertical acceleration).

Dividing both sides of (1) by  $dt$  gives,

$$F \frac{dz}{dt} = mg \frac{dz}{dt} + \frac{d}{dt} \left( \frac{1}{2} m \dot{z}^2 \right),$$

Carrying out time differentiation and using the chain rule for differentiation of the change in kinetic energy of the barbell gives,

$$F \dot{z} = mg \dot{z} + m \dot{z} \ddot{z},$$

Solving for acceleration gives,

$$\ddot{z} = \frac{F}{m} - g. \quad (2)$$

#### **Barbell + Rubber Band:**

For the following equation it is assumed that the resistance caused by the rubber band is linear and depends upon the stiffness ( $k$ ) and the displacement ( $z$ ). The work done on the barbell and rubber band is then equal to the sum of the change in potential energy of the barbell, the change in elastic energy of the rubber band, and the change in kinetic energy of the barbell respectively:

$$F dz = mg dz + d \left( \frac{1}{2} k z^2 \right) + d \left( \frac{1}{2} m \dot{z}^2 \right). \quad (3)$$

Dividing both sides of (3) by  $dt$  gives,

$$F \frac{dz}{dt} = mg \frac{dz}{dt} + \frac{d}{dt} \left( \frac{1}{2} kz^2 \right) + \frac{d}{dt} \left( \frac{1}{2} m\dot{z}^2 \right),$$

Carrying out time differentiation and using the chain rule for differentiation of the change in elastic energy of the rubber band, and change in kinetic energy of the barbell gives,

$$F\dot{z} = mg\dot{z} + kz\dot{z} + m\dot{z}\ddot{z},$$

Solving for acceleration gives,

$$\ddot{z} = \frac{F - kz}{m} - g. \quad (4)$$

### **Barbell + Chain:**

For the following equation the mass of the chain added to the barbell is expressed as  $\alpha z$ , where  $\alpha$  is the mass per unit length of chain. The work done on the barbell and chain is then equal to the sum of the change in potential energy of the barbell, the change in potential energy of the chain, the change in kinetic energy of the barbell, and the change in kinetic energy of the chain respectively:

$$F dz = mg dz + \alpha z g dz + d(0.5m\dot{z}^2 + 0.5\alpha z\dot{z}^2). \quad (5)$$

Dividing both sides of (5) by dt gives,

$$F \frac{dz}{dt} = mg \frac{dz}{dt} + \alpha z g \frac{dz}{dt} + \frac{d}{dt} \left( \frac{1}{2} m\dot{z}^2 + \frac{1}{2} \alpha z\dot{z}^2 \right),$$

Carrying out time differentiation and using the chain rule for differentiation of the change in kinetic energy of the barbell, and the product and chain rule for differentiation of the change in kinetic energy of the chain gives,

$$F\dot{z} = mg\dot{z} + \alpha z g\dot{z} + m\dot{z}\ddot{z} + \frac{1}{2}\alpha (\dot{z}^3 + 2z\dot{z}\ddot{z}),$$

Rearranging and using  $\ddot{z}$  and  $\dot{z}$  as a common factors gives,

$$\ddot{z}(m + \alpha z) = \dot{z} \left( F - g(m + \alpha z) - \frac{1}{2} \alpha \dot{z}^2 \right),$$

Solving for acceleration gives,

$$\ddot{z} = \frac{F - \frac{1}{2} \alpha \dot{z}^2}{m + \alpha z} - g. \quad (6)$$

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