Contemporary and novel assessment of biomechanics in plyometric and ballistic exercise and the implications for elite and recreational athletes.

Mark Jarvis

School of Health Sciences
University of Salford, Salford, UK

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Declaration

I declare that this PhD thesis has been composed by myself and embodies the results of my own course of study and research whilst studying at The University of Salford from August 2010. All sources and material have been acknowledged.

Abbreviations

ACL – Anterior Cruciate Ligament

BF – Biceps Femoris

BW – Body Weight

CMJ – Countermovement Jump

CNS – Central nervous system

CoM – Centre of mass

CON - Concentric

DJ – Drop jump

ECC – Eccentric

EMD – Electromechanical delay

GRF – Ground reaction force

IMP - Impulse

MTU – Muscle-tendon unit

MVIC – Maximum voluntary isometric contraction

PEC – Parallel elastic component

PEP – Peak eccentric power

PF – Peak force

RFD – Rate of force development

RSI – Reactive strength index

SDD – Smallest Detectable Difference

SEC – Series elastic component

sEMG – Surface electromyography

SSC – Stretch shortening cycle

TPA – Temporal phase analysis

VL – Vastus Lateralis

VO2 – Volume of oxygen

Abstract

Jumping exercises, comprising plyometrics and ballistic jumps, are commonly used and important in the development of athletic performance. However, our ability to describe training doses with accurate and meaningful measures lags significantly behind other forms of training. Furthermore, the assessment and understanding of the kinetic and kinematic characteristics which underpin effective performance are still emerging. This thesis begins by comparing methods of quantifying intensity and volume of such exercises. Measures of intensity which may be considered internal (muscle activation) and external (ground reaction forces) were compared across a range of commonly used jump exercises. It was concluded that intensity and volume may be best described through kinetic measures, namely relative peak ground reaction forces (PF) and relative net impulse respectively. The second study then applied this methodology to assess the kinetic performance of an elite group of track and field athletes in order to gain an understanding of the demands of plyometric exercise on elite performers. This highlighted the difference in PF experienced between high level athletes and recreational counterparts with elite athletes achieving relative PF in the order of double that seen in recreational subjects within the literature and the previous study. The methodology also included a more discrete assessment of PF within specific phases of the jump, described as impact, braking, concentric and landing phases, to extend previously described methods within the literature and increase the level of insight into the specific demands on an exercise. The highest forces were observed during the impact and landing phases whilst PF within the eccentric and concentric phases were comparable with each other for each given exercise. The final two studies of this thesis aimed to further the understanding of the biomechanical characteristics which underpin effective jump performance by applying a temporal phase analysis (TPA) to ballistic and plyometric exercise respectively . Comparisons of three distinct populations (elite jumpers, professional rugby players and recreational athletes) during ballistic exercise using this novel methodology provided further evidence to support the emerging picture of two alternative models of superior countermovement jump performance. The first of these is characterised by the superior neuromuscular capability of an athlete to produce concentric impulse within the timeframe of a jump. The second is characterised by an altered kinetic and kinematic signature with a greater negative displacement leading to the development of greater eccentric impulse and an augmented concentric phase. Finally, the novel application of the TPA to a drop jump demonstrated, for the first time, the efficacy of the TPA to provide additional insight into plyometric exercise. These results from an elite athlete population illustrated a model of effective drop jumping which was characterised by a brief ground contact time and stiff landing technique leading to greater force at zero velocity and an augmented concentric phase in comparison with a more compliant technique.

Chapter 1 – Introduction

The stretch-shortening cycle (SSC) is a commonly observed phenomenon involving a rapid lengthening of a muscle tendon unit, immediately followed by a rapid shortening (Komi and Nicol, 2010). The SSC can result in an augmented and more economical production of force during human movement. This has been demonstrated in both isolated muscle fibre studies (Cavagna et al., 1968, Cavagna et al., 1965) and in applied trials involving assessment of the SSC during human movement (Bosco et al., 1982a, Bosco et al., 1981, Bosco et al., 1982b, Bosco et al., 1982c, Bosco et al., 1982d, Aura and Komi, 1986, Ishikawa et al., 2005, Lai et al., 2014). The contribution of the SSC is estimated to be approximately half of the positive work involved in running and jumping activities (Cavagna et al., 1971, Verkoshansky, 1996). Consequently the SSC represents a critical component of human movement, particularly with regard to the performance of sporting activity.

The magnitude of SSC contribution to the production of work is affected by a number of factors including stretch velocity, muscle fibre type and coupling time (Heglund and Cavagna, 1985, Aura and Komi, 1986, Bosco et al., 1981, Kubo et al., 2000b, Toumi et al., 2004). The capacity of an individual to utilise the SSC can be considered trainable. Key mechanisms underpinning this process include tendon tissue quality (compliance vs. stiffness), muscular strength to resist yielding and the ability to achieve high levels of muscular activity prior to, and during, ground contact (Kyrolainen and Komi, 1995, Kubo et al., 1999, Ishikawa and Komi, 2004, Butler et al., 2003, Regueme et al., 2005, de Ruiter et al., 2006, Sullivan et al., 2009).

Those concerned with enhancing human athletic performance, be it towards greater speed and power, enhanced efficiency, or reduced injury risk may be well served by maximising their understanding of the training methods associated with the SSC. Plyometrics are an established training method which are characterised by a rapid overloading of the eccentric phase of movement to target the SSC (Potach and Chu, 2000). Mechanical overload is typically achieved through the product of gravity (modulated through drop height) and an

individual's body mass rather than added resistance. These exercises have been shown to be an effective means of enhancing jump and sprinting performance (Bobbert, 1990, Markovic, 2007, Taube et al., 2012, Alkjaer et al., 2013, Saez de Villarreal et al., 2012), improving running economy (Turner et al., 2003, Saunders et al., 2006), and reducing injury risk (Myer et al., 2005, Chappell and Limpisvasti, 2008, Yoo et al., 2010, Baldon Rde et al., 2014).

1.1 Rationale

Intensity is a key element in the quantification of training prescription - a critical process in order to plan and measure doses of work. Plyometrics lag behind other methods of training in this regard and are typically measured by crude or subjective means such as the height of drop from a box or a rating of perceived exertion.

A number of studies have sought to address the absence of an accepted measure of plyometric intensity using a variety of methodologies. The most commonly used approach is based upon kinetic evaluation of performance via ground reaction forces (McNitt-Gray, 1993, McNitt-Gray, 1991, Wallace et al., 2010, Wang and Peng, 2014). Whilst peak ground reaction forces are the most commonly used metric, researchers have also sought to explore more novel components of force such as eccentric rate of force development and peak concentric power (Jensen and Ebben, 2007, Ebben et al., 2011). This approach has also been extended to include specific joint contribution through inverse dynamics calculations (Sugisaki et al., 2013, Van Lieshout et al., 2014).

An alternative approach to kinetic assessment has been pursued through the measurement of muscular activation via sEMG (Ebben et al., 2008, Peng et al., 2011). This has produced contrasting findings to kinetic evaluation, suggesting that intensity should be considered from a multi-factorial perspective. Cappa and Behm (2013) demonstrated that large changes in muscle activation patterns can result from minor adjustments in kinematics, adding to the need for a broad picture.

It is clear that the prescription of plyometric exercise would benefit from an objective measure of intensity which describes the level of stress being placed on the athlete. To date, no consensus has been reached either in the literature or in applied settings as to the most appropriate means of defining such a metric. It would appear that the most comprehensive view of intensity may be gained through taking a multi-factorial approach which evaluates kinetic and kinematic variables as well as an insight into physiological stimulation. This was the focus of the first study of this thesis which, to the author's knowledge, was the first to combine electromyography and ground reaction force data with a view to measuring intensity. Establishment of a means of quantifying the intensity and volume of plyometric exercise may enable coaches and practitioners to prescribe exercise doses with greater precision, and thus gain a greater capacity to understand training loads and the anticipated stresses and adaptive responses.

Having established a valid and reliable method of describing intensity, the second study applied this methodology to elite performers in order to seek greater understanding of the demands placed on this population and therefore inform prescription. The predominant subject cohort within the literature is composed of recreational or sub-elite athletes. Therefore an assessment of elite, international level athletes represented a novel and important investigation. The insights from this enquiry are not restricted to those involved with elite sports performance. Much of the training literature and prescription guidelines used with applied settings remains based upon the methods used with elite athletes within the Soviet Union in the 1960s (Verkoshansky and Siff, 2009). Consequently, a greater understanding of this population provides a contrast with non-elite groups typically used in research settings with the potential to highlight differences in training stimulus and subsequent prescription implications.

There is a recent and growing body of work within the literature which has demonstrated that those achieving superior performances in plyometric and ballistic exercises do so not only through the advantage of being able to produce greater physical outputs per se but through differing patterns of force application (Cormie et al., 2009, Cormie et al., 2008, Cormie et al., 2010b, McMahon et al., 2017a, McMahon et al., 2017b, McMahon et al., 2016). These new insights have been underpinned by a novel method of ground reaction

force analysis known as temporal phase analysis (TPA). The understanding of how the most effective jumpers apply force to greatest effect remains a gap within the current literature and is the focus of the third study which compared elite jumpers, professional rugby players and recreational athletes. Professional rugby players provide a useful comparison with elite jumpers as they can be considered elite athletes in comparison with recreational subjects but may lack both the genetic make-up and training background typical of elite jumpers. This was the first study to make such a three-way comparison as well as being the first to assess performance of elite level jumpers. This extension of recent studies provides greater insight into an optimal model of jump performance which informs coaching practices towards improved performance. The thesis concludes by applying the TPA methodology to a plyometric exercise challenge in the form of the drop jump. This represents a novel application of this methodology which to-date has been applied exclusively to ballistic exercises. The focus of this enquiry was to begin to explore the characteristics of high performing jumpers through this methodology. This served to validate the novel application of the methodology as well as providing new insight into the kinetic and kinematic model observed during effective drop jumping to inform coaching practice.

Chapter 2 - Literature Review

2.1 The Stretch Shortening Cycle

2.1.1 Overview

This section will present the concept and mechanisms behind the stretch-shortening cycle (SSC). This will include a review of the literature demonstrating the presence and magnitude of the effect both through isolated fibre studies and human movement assessment. The mechanisms which underpin the SSC are also discussed. A clear understanding of these factors is critical to the successful design of interventions targeted at SSC augmentation.

Human locomotion is powered by a mechanical system which combines contractile muscular work with elastic recoil of the muscle-tendon (MTU) (Heglund and Cavagna, 1985). This process is characterised by a cycle of eccentric lengthening of a pre-activated MTU, a brief isometric phase (amortisation), rapidly followed by a concentric shortening phase. This is described as the stretch-shortening cycle (SSC). The SSC extends beyond locomotion and is present in almost all human movement. Indeed, the SSC has been described as the "natural form of muscle function" in contrast to an isolated view of eccentric, isometric and concentric muscle actions (Komi and Nicol, 2010).

2.1.2 Scope and Scale of the SSC

The measurement of augmented force production during a SSC action over isometric conditions was first demonstrated in isolated muscle preparations by Cavagna et al. (1965, 1968). Isolated muscle fibres of frogs were assessed in an attempt to estimate the effect of eccentric work on a subsequent concentric action (Cavagna et al., 1965). This demonstrated an almost 3-fold enhancement in work output (4.65 g.cm in non-stretch conditions vs. 13.04 g.cm in pre-stretch conditions). Critically, this also illustrated the importance of the eccentric-concentric coupling time between the stretch and the contraction. When the coupling time was zero the elastic properties of the MTU could be utilised to the greatest

extent, after this point the potential elastic energy is rapidly lost, predominantly in the form of heat (Komi and Nicol, 2010).

In addition to the potential for enhanced work outputs, the SSC can also influence the mechanical efficiency of muscle actions. Heglund & Cavagna (1985) examined isolated rat muscle with differing fibre type composition. The muscles studied included extensor digitorum longus (EDL) which is composed predominantly of fast twitch fibres, and soleus which is composed of predominantly slow twitch fibres. Positive work efficiency, as defined by the metabolic input to mechanical output ratio, was approximately doubled with a pre-stretch versus isometric conditions. When comparing muscles, positive work efficiency following a pre-stretch was similar in both EDL and soleus (50% in EDL vs. 40% in soleus). The speed of contraction at which peak efficiency was achieved was markedly different (1 length.s^{-1} in EDL vs. 0.5 length.s^{-1} in soleus). These findings are important as they demonstrate that the influence of the SSC on muscle actions is not homogenous. The potential for performance enhancement via a SSC may vary according to the muscle fibre type and the speed of movement of the given task. This view is supported by human jumping studies which suggest that differing sarcomere cross bridge life times in fast twitch versus slow twitch fibres affects the utilisation of elastic energy (Bosco et al., 1982c). In applied settings this has led to the classification of movements as involving fast or slow SSC (Turner, 2010).

These isolated muscle studies use tetanised fibres and therefore an electronic stimulus rather than a voluntary contraction (Cavagna et al., 1968, Cavagna et al., 1965). This provides a reliable background for comparison of elastic contribution to augmented force production as conditions remain consistent without interference from voluntary motivation, motor skill, or peripheral neurological mechanisms such as the stretch reflex or Golgi tendon organ inhibition. Whilst this may be desirable in terms of determining elastic potential, it may represent a misleading view of the SSC as these factors must be considered during human movement, thereby reducing ecological validity of the findings.

Isolated muscle studies may represent the theoretical maximum enhancement available from a SSC, however, these conditions remove the requirement of motor skill to co-ordinate

inter- and intra-muscular eccentric and concentric actions to minimise coupling time. The ability to maximise pre-stretch activation is also controlled to a greater extent in isolated muscle stimulation trials. Consequently it is also necessary to evaluate the SSC in voluntary human movement. Running and jumping are two of the most fundamental aspects of human movement and both have the potential to utilise a SSC for greater force production and efficiency. It is suggested by Komi & Nichol (2010) that hopping has the greatest mechanical consistency across intensities and best fulfils the criteria of requiring pre-activity, a rapid eccentric phase and a brief coupling time.

During performance of sprint running in human subjects, it has been estimated that approximately half of the power produced can be accounted for through contractile muscular power with the remaining work being attributed to elastic recoil (Cavagna et al., 1971). In agreement, Verkoshansky (1996) estimates a 60% contribution of elastic energy to power production in the most efficient runners. Similar figures of around 60-70% have been seen in assessment of the contribution of elastic recoil to positive work produced in the ankle flexors during running (Lai et al., 2014).

The majority of studies within the literature have assessed the contribution of the SSC to jumping rather than running (Bobbert, 1990, Kubo et al., 2007, Markovic, 2007, Taube et al., 2012, Young et al., 1999). This is most likely due to the practical challenge of collecting data during rapid locomotion versus a relatively static jump task. However, data from Bosco et al. (1987) suggest that the elastic behaviour of the leg extensor muscles is similar in running and jumping when the speeds of muscle contraction are comparable. This is based on findings which demonstrated a significant relationship between the energetics of jumping with a pre-stretch and that of running ($r=-0.66$). These findings are supported by correlations of similar magnitude demonstrated by Hennessy & Kilty (2001) when comparing sprint performance with CMJ and depth jumping. This study correlated CMJ height and a drop jump index (height/contact time) with 30 m and 100 m sprint times. The drop jump index and 30 m times showed the strongest correlation ($r=-0.79$). Therefore, to some extent at least, the findings of the various evaluations of the SSC in jumping studies may be applied to other aspects of human movement beyond jumping.

Computer simulation using optimized muscle activation patterns during a drop jump exercise has estimated a 32% contribution of stored series elastic energy to power production in the push off phase (Bohm et al., 2006). Interestingly, this figure reflects the reported maximal performance gain of 20-30% when a jump is preceded by a SSC (Bosco et al., 1987).

As has already been seen in isolated muscle studies and running assessments, the velocity and amplitude of stretch is a key factor in the contribution of the SSC to jumping (Aura and Komi, 1986, Toumi et al., 2004). Bosco et al. (1982a) found mechanical efficiency to be around 39% in countermovement jumps with a small amplitude and high velocity of stretch. This decreased to 30% with larger amplitudes and to 20% when no pre-stretch was utilised. Similarly, the magnitude of elastic contribution to plantar flexion in isolation has been seen to range from 20-40% between slow and fast movements respectively (Kubo et al., 2000b). Bosco et al. (1981) also found that coupling times (which refers to the duration between the eccentric and concentric phases of movement) during countermovement jumping were highly associated with enhanced performance during the concentric phase. This is likely to be influenced by the skill of the athlete in rapidly combining the actions without undue pausing, the magnitude of the eccentric loading and the joint angles involved in the movement. In this study subjects performed CMJ with self-selected technique with coupling times determined from the angular displacement and ground reaction forces. Average coupling times were 0.23 ms, similar to those used in isolated muscle trials. Minimising coupling times is an important consideration as this reduces the loss of potential elastic energy as heat.

Further insight into the role of movement velocity may be gained from an investigation of drop jumps from differing height (Ishikawa et al., 2005). Subjects performed jumps from a range of heights with the height resulting in the greatest rise in centre of mass being deemed optimal. Jumps were then performed from three different heights; optimal, low (optimal -10cm), and high (optimal +10cm). Real time ultrasound was used during all jumps to observe the behaviour of the MTU. When comparing trials of low, optimal, and high drop jumps the elastic contribution was diminished in the high condition. This was accompanied by a change in MTU behaviour with the fascicles lengthening which was in contrast to the

low and optimal height trials. It may be concluded that whilst increasing stretch velocities offer the potential for greater elastic strain to be achieved, this may only be realised when accompanied by a sufficient level of muscular force production to resist fascicle lengthening.

Lai et al. (2014) used data obtained from gait experiments in conjunction with musculoskeletal modelling and optimization techniques to calculate MTU work, tendon elastic strain energy and muscle fibre work for the ankle plantar-flexors at five speeds ranging from jogging to sprinting. These results demonstrate an increasing contribution of elastic sources to positive work with progressive running speeds moving from a slow jog (2 m.s^{-1}, 58% elastic contribution) to sprinting (≥8 m.s^{-1}, 75% elastic contribution). During both the running and jumping conditions evaluated in these studies, the observed muscle actions were isometric with length changes occurring at the tendon. Not only is this representative of the elastic model but it would suggest that contribution of the stretch reflex may not be significant due to the absence of a rapid fascicle lengthening. This does not entirely preclude the potential for muscle spindle activation as this may occur as a result of muscle "vibrations" but to a lesser extent than when actively lengthened (Cronin et al., 2011). It would appear that the importance of muscle fibre type is also evident in voluntary human movement as it is in isolated assessment. Bosco et al. (1982c) found that during vertical jumping, subjects with greater proportions of fast twitch fibres profited more from stretching phases characterised by high speed stretches with small angular displacements. During jumps with a larger amplitude and longer coupling time, subjects with a greater percentage of slow twitch fibres were better able to re-use elastic energy. This mirrors the findings of Heglund and Cavagna (1985) in which the efficiency of work in slow twitch fibres was maximised at slower speeds than fast twitch. The mechanisms behind this are discussed later in this chapter. The MTU behaviour characterised by an isometric muscle contraction and a lengthening tendon during the eccentric phase of a SSC also has implications for optimal muscle architecture. A shallow angle of muscle fibre pennation presents the opportunity for a greater velocity of shortening as a greater number of sarcomeres are positioned in parallel. However, in the absence of significant fascicle shortening, the greater contraction velocity available through a reduced pennation angle may be of little benefit. Conversely, a greater pennation angle which presents more sarcomeres in series may

enhance the capacity to produce force and resist lengthening thereby taking advantage of tendon recoil under greater forces.

2.1.3 Mechanisms Underpinning the SSC

Debate still exists around the nature of the mechanisms which contribute to the potential of an SSC to increase work output and efficiency in muscle actions. Three primary theories have been proposed, these are broadly described as storage of elastic energy, neurophysiological factors, and working range (Wilson and Flanagan, 2008, Turner, 2010).

The elastic structures of a MTU can be subdivided into the series elastic component (SEC) and parallel elastic component (PEC) (Hill, 1938). The PEC comprises the sarcolemma and muscle fascia and is responsible for resisting stretch at the end of range in a passive muscle. Storage of elastic energy within an active MTU takes place in the series elastic component (SEC) which comprises the cross bridges, structural proteins and tendons. Tendons are elastic in nature meaning that these tissues have the capacity to stretch and recoil in a process of storage of elastic energy which is then reused as kinetic energy (Alexander, 2002, Ishikawa et al., 2003, Kubo et al., 2000b, Fukunaga et al., 2001). The means by which the muscle fascicles and the tendon tissue interact are crucial for achieving this potential for elastic recoil. In order to take advantage of the elastic properties of the tendon, the muscle fascicles must remain isometric or shorten (Roberts, 2002, Fukunaga et al., 2001). Such a relationship between fascicle and tendon allows a maximal utilisation of the elastic property of the tendon whilst allowing the fascicles to develop higher forces at a lower energetic cost due to the force-velocity relationship. During such a sequence, Fukashiro et al. (2006b) suggest that fascicles are more appropriately considered a force generator rather than a work generator, i.e. task of the musculature is to produce high levels of force to resist movement rather than to produce it directly.

This relationship offers the further advantage that tendons have the capacity to shorten at a greater velocity than muscle contractions and therefore movement in high speed activities may be enhanced (Alexander, 2002). As pre-stretch velocities increase, muscle fascicles begin to shorten to a greater extent (Ishikawa et al., 2003). This would appear to reach a

critical threshold, after which both muscle shortening and power production decrease (Ishikawa et al., 2005).

Whilst the simplistic view of tendons as elastic structures and muscles as force generators may be compelling, it may not tell the full story. When cross-bridges are formed between filaments and a stretch is applied there may be storage of elastic energy within the cross-bridge (Wilson and Flanagan, 2008). This mechanism has been explored further by Lindstedt et al. (2002) who suggest that muscles function as adaptable locomotor springs. The theory is presented that elastic storage within the MTU may exceed the capacity of the tendon alone with the difference being provided by the muscle itself. Lindstedt et al. (2002) speculate that the protein titin is responsible for this and that task dependent adaptation can be achieved in the development of stiffness or compliance. This emerging theory proposes that forces during eccentric contractions exceed those which can be associated with actin and myosin and that the visco-elastic properties of titin may, at least in part, account for these forces (Herzog et al., 2014, Herzog et al., 2015).

In addition to the volitional contraction required for human movement, the tension generated by a muscle during a SSC is also the result of competing reflexes, namely the muscle spindle and the Golgi tendon organ (Zatsiorsky and Kraemer, 2006). These sensory receptors lie locally to the MTU and provide afferent feedback to the CNS. Whilst the muscle spindles lie parallel to the fascicles, the Golgi tendon organs are connected to extrafusal fibres within the tendon. The muscle spindle offers the possibility of potentiated activation of the muscle as a result of the rapid stretching of the muscle spindle (stretch reflex). This is in contrast to the inhibition of activity by the Golgi tendon organ in response to a lengthening of the tendon as a result of high muscular tension. Therefore coaches hypothesise that regular exposure to plyometric type training will result in a suppression of the Golgi tendon organ inhibitory response and an increase in the magnitude of stretch reflex. Such a phenomena may be the result of an adaptation to the neurological response through familiarisation or simply an increase in tendon stiffness requiring greater forces to stimulate the golgi tendon organ.

In addition to these local muscular structures which influence the reflex activity, the significance of spinal level influences via the H-reflex during short latency response have also been explored (Leukel et al., 2008b, Taube et al., 2008, Leukel et al., 2008a). Leukel et al. (2008b) assessed H-reflex excitability from low (31 cm) drop jumps and excessive (76 cm) heights. They found a reduction in H-reflex excitability when performing drop jumps from so-called excessive heights. This is suggested as a protective mechanism to reduce the loading on the MTU during movements of high force and velocity, independent of local muscle reflexes. This research leaves a number of unanswered questions around the factors which determine an excessive drop height and a subsequent inhibition. This may be simply a factor of the athlete's perception of the task. The determination that the greater height is "excessive" is also entirely subjective and the non-athletic status of the subjects would suggest that they were not familiar with exercise challenges of this nature. This is important as conclusions around a protective effect are based upon the assumption of excessive height. The study does demonstrate, however, that neurophysiological influences on SSC performance extend beyond the structures within the MTU, namely the muscle spindle and Golgi tendon organ.

In summary, the level of neural activation within a muscle during a SSC is the sum of the volitional activity plus or minus the net yield of these competing reflexes. Peak performance would seem to occur when maximal athlete intent is augmented by a potentiated muscle spindle with minimal inhibition from local and central protective mechanisms.

Previously, elastic energy contribution and neurophysiological factors have been generally regarded as the primary contributors to augmented SSC performance. However, more recently it has been argued that the opportunity to develop a greater active state is a major factor in the enhanced performance seen following a pre-stretch (van Ingen Schenau et al., 1997, Bobbert and Casius, 2005, Bobbert et al., 1996b, Walshe et al., 1998). The activation of muscle tissue prior to a concentric phase provides an opportunity to overcome electromechanical delay. It is suggested that maximal muscle tension may take around 0.6-0.8 s to generate (Edman, 2003). Therefore there is a greater opportunity to achieve levels of muscular tension closer to maximum which is unlikely to be achieved prior to take off in a jumping task given the constraints of movement time. Finally, fascicles are able to operate

more efficiently through an isometric contraction when compared with conditions without a pre-stretch due to the tendon-fascicle interaction described previously (Ettema et al., 1992). The utilisation of greater active state to augment performance may be achieved through a SSC or through an isometric pre-load, thus demonstrating independence from elastic contributions (Walshe et al., 1998).

The active state theory has been explored when comparing countermovement jump (CMJ) with squat jump performance (Bobbert and Casius, 2005, Bobbert et al., 1996b). Human jump data comparing squat jumps and CMJ was used in both of these studies to inform a computer simulation of jumping. The model concluded that the increases in jump height seen in CMJ versus squat jump were a result of more work produced over the initial 30% of the shortening phase, primarily produced by the hip extensors with the source of this being a higher active state and force production prior to shortening. These studies argue that elastic energy does not play a major role in the augmented performance seen in the CMJ. This may be explained by the large amplitude of movement, lower angular velocities and longer coupling time typically demonstrated during these jump tasks in comparison with shorter SSC tasks such as a drop jump or hop. The theory regarding active state is compelling however further research is required to demonstrate this beyond a simulation model.

2.1.4   Trainability of the SSC

Those concerned with the science of training individuals, be it for purposes of rehabilitation or enhanced performance in sports, require an understanding of the contributing factors to the SSC effect which are adaptable through training. A thorough understanding of the nature of adaptations following training and their potential magnitude is critical if training programme design is to be optimised.

In order to achieve the optimal fascicle-tendon interaction, the presence of a high efferent neural drive prior to an induced stretch, typically through a contact between the feet and the ground, is fundamental to achieving a SSC (de Ruiter et al., 2006). Given that pre-activity in muscle inherently occurs prior to an external stimulus, it seems reasonable to conclude

that this is a modifiable phenomenon based on the ability of an individual to both perceive the requirement for pre-activity and to action an optimal response. Avela et al. (1996) compared the neuromuscular characteristics of gastrocnemius and soleus across a range of jump challenges. The study used drop jumps (29, 46, and 66 cm), sledge jumps performed on special apparatus which allowed manipulation of load (body mass, plus 20%, and minus 20%, and lifting block jumps which allowed manipulation of acceleration (gravity, plus 20%, and minus 20%). These variations allowed modification of the loading of the leg extensors. The results demonstrated that the duration of pre-activation varied between different jump challenges with eccentric peak angular velocity of the ankle joint being related to the magnitude of preactivation. The authors concluded that whilst the fundamental skill of pre-activation may be an inherent human instinct it may be modified through proprioceptive, vestibular and visual inputs. In parallel, activation may be inhibited at the spinal level when jumping from excessive heights through changes in the H-reflex as previously discussed (Leukel et al., 2008b). This supports the view that the perception of the individual plays a role in determining the level of pre-activation, both in terms of the ability to interpret the requirements of a task and the absence of fear to prevent inhibition. The case is supported by the findings that pre-activity is often absent or minimal during an unanticipated fall (Santello, 2005).

This view of pre-activation as modifiable event controlled, at least in part, by cognitive interpretation of a task is further supported by studies which have evaluated the response to a range of tasks. Ishikawa et al. (2003) and Ishikawa and Komi (2004) have shown progressive increases in electromyographic preactivity during drop jumping as the drop height is increased with a concomitant increase in reliance on tendon elasticity for force production. Both of these studies used drop jumps performed on sledge apparatus to control drop heights with MTU behaviour assessed using real time ultrasonography. Surface EMG activity increased in both the preactivity and braking phases but reduced during the concentric phase (the phases of such jumps are illustrated in Figure 2-1). This pattern was accompanied by a reduction in fascicle lengthening and an increase in tendon lengthening with greater drop heights. This demonstrates the important role of preactivity in the utilisation of elastic energy. A television monitor was used to provide visual feedback with subjects instructed to achieve a consistent knee angle of 105°. The same mechanism was

used to elicit a consistent jump height across trials. Neither of the subject groups were trained athletes and therefore the use of the sledge may be important in order to mitigate against the complication of poor and inconsistent technique. In addition to the modulation of the efferent response based on perception, afferent sources may also influence the motor patterning of an event.

Regueme et al. (2005) examined the neuromuscular response following exhaustive SSC exercise using submaximal loads on a sledge apparatus. Plantar flexion rebound exercise on the sledge was used to target the soleus muscle. The authors found a decrease in soleus force during maximal isometric plantar flexion testing and an increase in pre-activity of the soleus during rebound exercise both immediately post-exercise and 2-days later . This may suggest that musculo-tendinous damage influences the subsequent efferent neural response to a SSC challenge. The subjects also demonstrated a shift from enhanced soleus activation in the braking phase post-exercise to an increase in the concentric phase at 2-days. This was accompanied by an increase in medial gastrocnemius activation at 2-days. These results support an altered efferent neural response to afferent feedback in SSC exercise. It should be noted that an evaluation of the experimental group was not conducted prior to the exhaustive protocol and inferences were made based on the performance of the control group. Both groups were small (n=6) and therefore further replication of these findings is required with pre-fatigue performance measured.

Finally, power athletes have been shown to have more rapid and larger pre-activation responses when compared with endurance athletes (Kyrolainen and Komi, 1995). These characteristics support superior explosive performance in the power athletes. Similarly, repeated SSC exercise in the form of drop jumps on a sledge apparatus demonstrated greater mechanical efficiency in endurance athletes than power athletes (32.8% power vs. 46.8% endurance). It is not clear if these differences are the product of genetics or acquired through associated training methods. It has been hypothesised that the greater ground reaction forces involved in explosive events such a sprinting require a greater level of neuromuscular pre-activation and in turn training efforts may act as a stimulus for a greater ability to preactivate (Zehr and Sale, 1994). Kyrölänen et al. (1991) investigated the effects of a power training programme consisting of various jumping exercises on nine healthy

women. After adhering to the programme 3 times per week for 4 months, the subjects showed higher preactivation of the leg extensors during sledge apparatus testing, thus illustrating an adaptive training response. This is often suggested as a contributory factor in the enhanced postural control seen following neuromuscular training towards reduction of anterior cruciate ligament injury (Yoo et al., 2010, Chappell and Limpisvasti, 2008, Myer et al., 2005).

Introductory text books have traditionally proposed that an effect of frequent exposure to high SSC loads through training is a down-regulation of the inhibitory effects of the Golgi tendon organ, also described as disinhibition (Potach and Chu, 2000). This theory is challenged by Chalmers (2002) who suggested that direct evidence of such a training adaptation has not been shown in human or animal studies. The theoretical Golgi tendon organ disinhibition may be accompanied by an augmented potentiation via the muscle spindle (Bosco et al., 1982b). The combined effects of these two phenomena, or either in isolation, would be represented by increased muscle activity. Such evidence however does not provide a direct link to these specific mechanisms. Where such an effect has been seen it is generally accompanied by changes in the duration and rate of pre-activity. As this effect occurs prior to muscle stretch and load acceptance it is clearly driven by the CNS. This does not preclude an additional potentiation or disinhibitory contribution locally but the existence of such an effect in isolation remains unclear.

A compliant tendon is required to achieve elastic strain associated with SSC (Kubo et al., 2000b, Fukashiro et al., 2006a, Lichtwark and Barclay, 2010). To take advantage of the mechanical properties of a compliant tendon the ability to produce sufficient muscular force to resist lengthening of the fascicles is also required. This must be considered when evaluating studies of isolated tendon behaviour as the behaviour of the MTU as a whole will determine the subsequent mechanical outcome during activity. Human movement requires a balance between tendon compliance and stiffness (Butler et al., 2003). An overly compliant tendon may hinder force transfer in high force, high velocity concentric actions and also increases the risk of injury due to tissue elongation (Wilson et al., 1991, Wilson and Flanagan, 2008). Conversely, tendon stiffness is inversely correlated with pre-stretch augmentation associated with a SSC during jumping (Kubo et al., 1999). The task and joint

specific nature of muscle-tendon stiffness can be seen in comparisons of behaviour of the knee extensors and plantar flexors during running. Kubo et al. (2000a) compared male sprinters with strength matched controls during isometric knee extension and plantar flexion exercise. These findings demonstrated a greater degree of tendon elongation in the sprint group during low loads in knee extension but this was not apparent when loads exceeded 50% of maximal voluntary contraction. Elongation of the vastus tendon was negatively correlated (r=-0.76) with 100m sprint time. In contrast, there was no difference between sprinters and controls in gastrocnemius compliance during plantar flexion between groups, nor was there a correlation with sprint performance (r=0.23). These comparisons provide insight into the nature of MTU stiffness in high force tasks. Consideration should be given to the single-joint, isometric nature of these tests in contrast to typical multi-joint dynamic activity common in human movement. A joint specific compliance-stiffness requirement has also been demonstrated in endurance running. Kubo et al. (2015) examined a large cohort (n=64) of highly trained long distance runners. Elongation of tendon structures of the knee extensors and plantar flexors was evaluated over ramp isometric contractions up to a maximal effort using ultrasonography. Muscle force and tendon elongation was fitted to a regression slope and compared with the best 5000 m record. This time was negatively correlated with stiffness of the tendon structures in the knee extensors (r=-0.34) whereas it was positively correlated with stiffness of the plantar flexor tendon structures (r=0.41).

Tendons respond to loading through enhanced collagen synthesis and increased stiffness (Miller et al., 2005, Sullivan et al., 2009). Kubo (2007) compared the effects of resistance training and plyometric training on tendon stiffness and joint stiffness following a 12-week (4.d.wk^{-1}) plantar flexor programme. Subjects performed heavy unilateral plantar flexion resistance training on one limb (80% 1RM) and plyometric training (drop jumps and hops) on the opposite limb. Tendon stiffness was assessed using ultrasonography during isometric plantar flexion. The validity of an isometric assessment of tendon adaptation to highly dynamic plyometric training may be questioned. Joint stiffness was measured during ankle movement only sledge jumps and was calculated as the change in joint torque divided by the change in ankle angle during eccentric phase. It is unclear why this methodology was not also used to assess tendon specific stiffness changes. Resistance training resulted in

significant increases in tendon stiffness whereas the plyometric training did not. Conversely, joint stiffness did not change following resistance training but increased significantly following plyometric training. Foure et al. (2010) found a trend towards increased stiffness in the Achillies tendon following 14 weeks of plyometric training. The training protocol comprised a total of 34 sessions of 200-600 jumps resulting in a total of approximately 6800 jumps over the 14 week period. This would typically be regarded as a very high training volume when compared with training guidelines which describe 100-200 jumps as being a typical range (Potach and Chu, 2000). The low subject numbers (training group n=7) and subsequent poor statistical power of this study may have resulted in the failure to detect a statistically significant difference as a mean increase of 24.1% in tendon stiffness was observed. The reason for the contrasting findings of these two studies is unclear given that the training protocols and testing procedures were comparable. It is possible that the absence of a change in tendon stiffness as seen by Kubo (2007) and the variability of subject response found by Foure (2010) reflects the varied training status of the subject groups.

Structural adaptations to tendons are known to be related to the degree of mechanical strain (Arampatzis et al., 2010) and therefore this is a key component of a training programme targeted at tendon adaptation. Resistance training involving large mechanical strain due to the duration of muscle contraction typically provides greater opportunity for accumulated strain than plyometric training which typically involves brief and rapid contractions. The discrepancy between changes in tendon properties and joint mechanics illustrated by Kubo et al. (2007) highlights the need to consider the MTU as a whole in human movements as well evaluating the tendon in isolation. Training adaptations seen at a gross level, such as joint stiffness, may be incongruent with isolated tissue adaptations and therefore coaches should be cognisant of this when designing training regimes. As has been discussed previously, elastic muscle properties may be regulated via the adaptation of titin filaments (Lindstedt et al., 2002). However, as Zatsiorsky and Kraemer (2006) suggests, muscle stiffness is highly variable due to the ability to activate or relax, whereas tendon stiffness is constant (in an acute sense).

2.1.5 Summary

It is clear that the SSC has the potential to enhance work outputs and increase mechanical efficiency in human movement. The significant magnitude of this phenomenon has been demonstrated across isolated study of muscle and in assessment of various whole body movements. The magnitude of this contribution to positive power production is dependent on several factors. However, the elastic recoil of the MTU may be reasonably considered to contribute up to and beyond 50% of the positive work performed. Key factors in determining this include the velocity and amplitude of the stretch and the muscle fibre types involved. A rapid stretch velocity is desirable in order to maximise the elastic potential of the MTU. A brief coupling time may prevent the loss of this potential elastic energy and therefore conditions of smaller amplitude of stretch may also be considered optimal. As velocity decreases and amplitude increases the contribution of elastic energy is likely to reduce and a less economical positive work production via muscular contraction will be relied upon.

The SSC has been established as a phenomenon of great significance to human movement and has the capacity to be augmented through training interventions. The following review will explore the factors associated with training and consider the key characteristics of effective training methodologies and their efficacy in enhancing specific aspects of human performance.

2.2 Plyometrics and the Efficacy of Jump Training

2.2.1 Overview

Having explored the concept of the SSC previously, this section will discuss the use of plyometric exercise to overload the SSC and enhance human movement performance. Initially this will begin with a review of the aspects of performance which may be enhanced through plyometrics and the relative magnitude of change achievable. This is followed by an examination of the nature of adaptation which occurs following a period of plyometric training. This section will make the case for plyometrics as an important tool in development of human movement.

Plyometrics are a popular and well established category of exercises which are designed to take advantage of conditions which enable utilisation of the SSC to augment subsequent dynamic muscle actions (Potach and Chu, 2000). Used primarily towards the enhancement of sports performance through augmented and more efficient locomotion, they are characterised by rapid eccentric-concentric muscle contractions. Targeted adaptations to plyometric exercise place a large emphasis on neural factors and changes to elastic components of the muscle-tendon unit as well as the contractile element. This is in contrast to other traditional forms of training, such as resistance training, which may place a greater emphasis on tissue adaptation (Pfaff, 2010, Cormie et al., 2010a, Folland and Williams, 2007). The exercises involved are typically based around jump-type movements but may also include sprints and throws (Schexnayder, 2010). With regard to jumps and sprints, a key feature of these methodologies is that the product of the athlete's body mass and gravity provide the mechanical overload stimulus rather than an external load such as a barbell. These loadings may be modulated through the use of varied drop heights to increase the velocity at ground contact and through augmented loading via weighted vests or light barbells.

Plyometrics were first formally used in the 1960s by Soviet sports scientists who originally described a method of jump training as the "shock method" (Gambetta, 1998,

Verkoshansky, 2012, Verkoshansky and Siff, 2009). These methods were focussed primarily on the use of plyometrics as a specific tool for the enhancement of explosive performance, such as maximal sprinting, jumping and throwing. However this somewhat limited view may fail to consider the role of the SSC and plyometrics in enhancing mechanical efficiency and therefore economy of movement in submaximal activity.

2.2.2 Efficacy of Plyometric Training

Possibly as a result of the origins of plyometric training, a primary focus within the literature has been to evaluate the effects of plyometric training on vertical jump performance. The most common intervention used within these studies is the drop jump, the results of which were reviewed by Bobbert (1990). A review of 15 studies revealed typical gains in CMJ height of around 4 cm based on 8 weeks of drop jump training 2 times per week. This would broadly suggest that the augmented eccentric overload provided by dropping from a box provides sufficient stimulus to provoke adaptation resulting in improved performance in the CMJ. The drop heights used across these studies range from 30-110 cm although this does not appear to have a relationship with performance gains. The level of skill of the subjects does not appear to contribute with similar performance gains demonstrated in studies evaluating skilled and unskilled jumpers. The range of training methodologies and volumes varies significantly across these studies with no particular trends evident. Therefore a deeper understanding of the training variables and precision of training prescription may be difficult to draw from this evidence.

Greater insight may be gained from an investigation by Taube et al. (2012) who demonstrated that despite performance gains being similar, the use of moderate to high drop heights may provoke different neuromuscular adaptations to lower heights. Unskilled subjects who participated in a 4-week drop jump training programme using moderate to high heights (50-75 cm) showed a significant increase in rebound height with an increase in ground contact time. In contrast, subjects using low drop heights (30 cm) showed only a trend towards increasing rebound height but reduced ground contact time. A performance index (rebound height/ground contact time) revealed a homogenous performance gain (14%) across both protocols. The differing nature of performance adaptation was reflected

in muscular activation with mod-high group showing significantly increased soleus activity (28%) close to take off (120-170 ms) whereas the low group significantly increased activity (30%) shortly after ground contact (20-70 ms). This is an important distinction as the nature of adaptation may often be of greater importance in a training regime than the gross output alone, for example in rehabilitation versus performance enhancement settings. These performance gains have been replicated in national level power athletes by Alkjaer (2013). A 4-week training protocol based on the Taube study provides an insightful comparison. Similar gains were found in the performance index (16%) with an apparently similar mechanism characterised by an increase in soleus activity shortly after ground contact (45 ms). It is noteworthy that the performance gains were not accompanied by any changes in isometric or isokinetic performance in plantar flexors, knee extensors and knee flexors as assessed by dynamometry. This would suggest that performance gains in jumping can be achieved primarily through neural factors regulating the activation pattern controlling the drop jump movement. The drop height used was adjusted individually to give a landing velocity of 2.5 m.s^{-1}). This was achieved through the use of an infrared grid placed 10 cm above the force platform to calculate velocity. The actual drop height used was 30.0-36.5 cm which would generally be considered low for an elite power population and it is unclear whether greater performance gains may be achieved when subjected to a greater drop velocity.

The training status and pre-existing neuromuscular qualities of an athlete may influence the capacity for training adaptations following plyometric exercise. Cormie et al. (2010c) investigated the magnitude and mechanisms of adaptation in stronger versus weaker individuals to ballistic power training. The study used loaded jump squats which are rightly categorised as ballistic rather than plyometric. However such methods do represent an overload of the SSC and therefore results may transfer to plyometric training although such differences should be considered. Although there were no statistically significant differences between the groups, what were described as "practically relevant" effect size differences were observed in key variables after 5 weeks (effect size: stronger: peak power = 1.60, jump height = 1.59; weaker: peak power = 0.95, jump height = 0.61). This study replicates the previous findings of the same group (Cormie et al., 2010b).

A key finding from both studies is the nature of adaptation to ballistic power training which made more effective utilisation of the eccentric phase of a CMJ. This mechanical change is characterised by more rapid de-loading during descent to provide a greater loading to elastic structures. It is hypothesised that this alternative jump strategy, rather than physiological adaptation per se, is the key driver of performance gains following this training. Such a technique is suggested to enable greater utilisation of so-called "eccentric strength reserves". This phenomenon would provide an advantage to stronger individuals who are better equipped to counter a rapid de-loading with sufficient joint stiffness and subsequent elastic recoil. A rapid unweighting, characterised by a greater negative velocity, must be countered by a corresponding increase in braking impulse if the duration of eccentric phase and depth of displacement are to be maintained. Consequently this technique favours those with greater eccentric strength capacity who are able to respond to the demand for greater braking impulse. This theory requires further exploration and the transfer of such effects to plyometric training also requires further study. However these results present a viable theoretical model for greater gains following SSC overload training in stronger individuals.

Whilst drop height and subject training status have historically been key considerations within the literature, the technical instruction given to the athlete is rarely discussed. An investigation by Marshall and Moran (2013) compared the "countermovement" drop jump (CDJ) and the "bounce" drop jump (BDJ). For the CDJ subjects were instructed to jump for maximum height whilst the BDJ were instructed to achieve minimal ground contact time. These techniques can be further distinguished by differing kinematics. Whilst no specific instruction was given in this regard, subjects displayed greater angular displacement at the hip (77 ± 15° vs 119 ± 13°) and knee (90 ± 7° vs 101 ± 8°) during CDJ than during BDJ whilst plantar flexion was consistent. An 8-week training programme resulted in gains in CMJ height of 6% (2.9 ± 2.6 cm, $p<0.05$) for those jumping for the CDJ group but no significant change for the BDJ group (-0.2 ± 2.6 cm, $P>0.05$).

These results would seem logical given the kinematic profile of CMJ, CDJ and BDJ. Joint angles at hip and knee, jump amplitude and jump duration all followed a pattern of CMJ>CDJ>BDJ. As a result a greater transfer of performance gain may be expected between

CDJ and CMJ than BDJ. Furthermore the use of a CMJ to assess training gains does not allow evaluation of an enhanced ability to reduce contact times which was the primary intent of the BDJ subjects. The results highlight the importance of technical execution and instruction in training adaptation and should therefore be considered in both research and training settings. It may also be useful to consider and report kinematic data in research studies to provide greater insight into jump execution beyond the broad descriptors commonly used.

In addition to the use of drop jumping, mixed plyometric training protocols have been evaluated with regard to the impact on vertical jumping performance (Markovic, 2007). A meta-analysis of 26 studies revealed a mean effect on jump height of 4.7% (SJ), 8.7% (CMJ) and 4.7% (DJ). The meta-analysis approach is a useful one in the context of plyometric research as studies typically rely on low subject numbers and therefore the statistical power may be insufficient to demonstrate statistical significance. Furthermore the number of variables in plyometric studies including training protocols, subject background and outcome measures makes comparison difficult. The findings from this study support the use of plyometric training to enhance jump performance.

The superior gains in CMJ over SJ are logical given that the SSC is absent in the SJ. However the modest improvements in DJ in comparison with CMJ are somewhat surprising given that the DJ utilises a more intense SSC. Interpretation of these findings is difficult due to the number of studies involved and the range of subjects. However the lower skill level and likely greater familiarity with the CMJ may provide a more sensitive means of demonstrating adaptation. The wide range of plyometric exercises used in these studies illustrates that drop jumps are simply one of many plyometric options for improving jump height. This point is reinforced by Markovic et al. (2007) who found that sprint training and plyometric training produced similar gains in jump performance. However it should be noted that the methodology presents significant problems in comparing training load and volume across modalities and may not be considered to be accurately matched. The volume of training within a single training session is often regarded as a key consideration in programming with ground contacts typically recommended as being capped around 100-120 per session (Potach and Chu, 2000). The mean number of contacts per session in Markovic's meta-analysis was 77 which can be considered low-moderate.

Cadore et al. (2013) evaluated the neuromuscular, metabolic and hormonal response to plyometric training volumes of 100, 200, and 300 ground contacts per session. Eleven elite male rugby players did not show any difference between responses to these volumes with fatigue being evident 5 minutes, 8 hours and 24 hours post-exercise. A smaller volume intervention may have proved an insightful addition as the lowest number of jumps used (100) still represents a significant stimulus which may be unfamiliar to this population. Consequently the players may have exceeded a threshold in the lowest volume protocol after which further fatigue may not be detectable in a small sample size.

The extensive use of jump training as a means of plyometric stimulus is often based on a relationship with sprint performance rather than solely on vertical jump gains, the benefit of which may be somewhat limited in sports performance. Relationships have been demonstrated between sprint performance and both CMJ (30 m sprint, r=-0.60; 100 m sprint, r=-0.64) and DJ (30 m sprint, r=-0.79, 100 m sprint r=-0.75) (Hennessy and Kilty, 2001).

Peak force during CMJ has also been shown to be predictive of sprint times in elite sprinters (r=0.-83) (Markstrom and Olsson, 2013). Saez de Villarreal et al. (2012) performed a meta-analysis of 26 studies to evaluate the impact of plyometric training on sprint performance. Whilst this review concluded that plyometric training is an effective method of developing sprint performance, only loose conclusions can be drawn with regard to the specific contributory factors. This is due to the limitations of the literature through the use of mixed subject groups, small sample sizes and varied training programmes. The authors suggested that the greatest impact was to be found over the initial 10-40 m of a sprint. This is in contrast to the view that the use of elastic energy is low at the start of a sprint and increases to its highest point during top speed running (Cavagna et al., 1971). This may in part be explained by the use of non-elite sprinters in many studies who are likely to reach top speed sooner than elite sprinters. However, as is evident in the gains seen in SJ following DJ training, the performance gains from plyometric training may not be restricted purely to the SSC. This would suggest that a transfer effect is evident whereby adaptations, be they central or peripheral, enable augmented performance during actions in which the SSC plays

a less significant role in force production. These adaptations may include greater tendon stiffness for transfer of force, greater intermuscular coordination and enhanced neural drive, although it should be noted that these are merely proffered as a hypothesis.

One of the largest performance gains demonstrated within the literature was seen in young male soccer players (age = 19) (Chelly et al., 2010). This group completed 8-weeks of in-season plyometric training and increased peak running velocity at 5 m (pre=4.0±0.5 m.s.$^{-1}$, post=4.4±0.4 m.s.$^{-1}$) and at 40m (pre=8.2±0.2 m.s.$^{-1}$, post=9.0±0.2 m.s.$^{-1}$) in contrast with a control group who made no improvement. The players trained twice per week using a progressive programme which adhered to typical guidelines around intensity and volume. The efficacy of this programme may have been complimented by a cohort of subjects with an established training base but minimal exposure to this specific stimulus, consequently the potential for gains may have been maximised. A sprint-specific plyometric programme over 8-weeks (15 sessions in total) investigated by Rimmer and Sleivert (2000) found greater gains in 10 m and 40 m sprint times in a plyometric training programme versus a sprint training programme. Whilst this may further demonstrate the efficacy of plyometric training, caution should be exercised with regards to comparisons with sprint training as no performance enhancement was achieved following the sprint protocol. Given that sprint training is an established methodology for enhancing sprint performance the failure to elicit a performance enhancement in this instance may reflect a failing in the methods of the specific programme.

An analysis of 20 m sprint performance in a highly trained group of sprinters (100 m time = 10.89 ± 0.23 s) provides greater insight into the specific adaptations which may underpin enhanced sprint performance following plyometric training (Mackala and Fostiak, 2015). Following 2 weeks of plyometric training, sprinters improved performance via an increased stride frequency (pre = 4.31±0.2 Hz, post = 4.39±0.2 Hz) which was achieved through reduced ground contact time (pre = 138±18 ms, post = 133±19 ms). These changes were not accompanied by alterations in stride length and therefore resulted in a net gain in speed. Such an effect would be consistent with a more effective use of the SSC as may be expected from a plyometric training programme.

Verkoshansky and Siff (2009) argue for a broad definition of plyometrics, both in terms of the exercises used and the scope for performance gain. This is supported by studies in young soccer players demonstrating that a wide range of plyometric interventions including bilateral, unilateral, horizontal and vertical improved agility and sprint performance as well as kicking velocity (Ramirez-Campillo et al., 2014a, Ramirez-Campillo et al., 2014b, Ramirez-Campillo et al., 2014c). In agreement, when reviewing performance adaptations to lower body plyometric training Markovic and Mikulic (2010) conclude that: "plyometrics, either alone or in combination with other training modalities, have the potential to enhance a wide range of athletic performance (i.e. jumping, sprinting, agility and endurance performance) in children and young adults of both sexes", (p.889).

As discussed previously, the view of plyometrics solely as a means of improving performance in explosive actions may be somewhat limiting. Lichtwark and Barclay (2010) demonstrated the capacity of tendons to act as energy conserving springs using an in situ muscle-tendon preparation. A series of ramped stretches at increasing velocities showed a decoupling of fasicle length changes to that of the MTU with progressively greater levels of energy being absorbed by the tendon with increased stretch velocity. Such phenomena produces greater work efficiency by enabling muscles to remain closer to optimal length and reducing metabolic cost of work. Studies using short-term (6-9 weeks) plyometric training in endurance runners have demonstrated performance gains through enhanced running economy (Turner et al., 2003, Saunders et al., 2006). Both of these studies used a protocol involving the addition of plyometric training to an existing training regime in an experimental group whilst continuing with normal training in a control group. Therefore it is not possible to compare the benefits of introducing plyometric sessions with a proportional increase in normal training volume. Such a comparison would provide insight as to whether gains were a result of the specific methodology or simply an increase in training volume. Running economy in both studies was measured through collection of VO_2 during a 3-speed treadmill protocol. The magnitude of performance gain from the experimental groups was similar in both studies with gains in running economy of 2-3% over 6-weeks (Turner et al., 2003) and 4% over 9-weeks (Saunders et al., 2006). In both cases these improvements were achieved without changes in VO_{2max}, thus suggesting that plyometrics may represent an opportunity for improvements in performance via mechanical adaptations in endurance

runners. The nature of these adaptations is unclear at present. Turner et al. (2003) found no change in jump test scores which were used as an indirect measure of the ability to store and reuse elastic energy. The choice of test may not have been optimal though as the subjects performed CMJ and squat jumps. The squat jump does not involve a SSC and the CMJ is not considered to make maximal use of the SSC (Bobbert et al., 1996a). In contrast, Saunders et al. (2006) found a 15% increase in power output during a 5-jump continuous test. The inclusion of task involving a rebound may replicate more closely the challenge placed on the MTU in running than the CMJ or squat jump. The training status of the athlete does not seem to be a discriminatory factor in performance improvements. Turner et al. (2003) evaluated regular but not highly trained runners whereas the subjects assessed by Saunders et al. (2006) were highly trained runners (mean $VO_{2max.}$= 71.1±6.0 ml.min^{-1}.kg^{-1}).

In contrast with the view of plyometrics as a high intensity, explosive activity, a significant focus has also been placed on the use of plyometrics for the development of motor control towards the reduction of injury risk. Sub-optimal mechanics, particularly during landing which is inherently a high force, high velocity action, are associated with injury risk (Dufek and Bates, 1991), particularly at the knee and ankle. The focus of the literature is dominated by the study of knee injuries with anterior cruciate ligament (ACL) injuries being the primary injury of interest. Hewett et al. (2005b) followed a cohort of 205 female athletes in high risk sports (i.e. those involving high speed changes of direction and landings). Of this group, 9 went on to suffer non-contact ACL injuries over the course of a competitive season. A number of biomechanical risk factors were identified when this group were compared with those who did not suffer an ACL injury. Knee abduction angle at landing and knee abduction moment were both greater in the ACL group. Further analysis of these data revealed that dynamic valgus measures provided a predictive r^2 value of 0.88. This study provides a clear link between ACL risk and landing kinematics as well as providing greater clarity as to the biomechanical patterns most likely to lead to injury.

Having established a pattern of biomechanical risk factors, recent focus has moved toward interventions to address high risk movement patterns. Myer et al. (2005) utilised a broad training programme consisting of plyometrics, core, resistance and speed training in 41 female team sport athletes. Subjects demonstrated increased back squat (92%) and bench

press (20%). Jump performance improved in single-leg hop (right leg = 165.1±3.0 cm pre, 175.5±2.6 cm post; left leg = 165.1±2.7 cm pre, 173.6±2.5 cm post), and vertical jump also increased (pre 39.9 ± 0.9 cm, post 43.2 ± 1.1 cm). Three-dimensional motion analysis demonstrated decreased knee valgus (28%) and varus (38%) torques following training. These results clearly demonstrate that some of the key biomechanical risk factors for ACL injury are trainable. However the mixed methods of training used within the intervention make specific conclusions regarding the efficacy of plyometric training difficult to draw.

A longer-term assessment of plyometric efficacy on female ACL injury risk was made by Mandelbaum et al. (2005). Regular warm-ups were replaced with a programme consisting of education, stretching, strengthening, plyometrics, and sports-specific agility drills in 1041 female team sport athletes (versus 1905 as controls). The intervention resulted in an 88% and 74% reduction in seasons 1 & 2. Once again, the mixed methods used in the intervention make it difficult to identify the precise mechanism behind this protective effect. However the large cohort is in contrast to the typically small subject numbers used in such studies and the duration of 2 full competitive seasons adds further illustration of a long-term effect.

A more discrete assessment of the impact of plyometrics on neuromuscular control was made by Myer et al. (2006) who compared plyometrics with balance training. Female athletes performed either of these modalities 3x per week for 7 weeks. Measures of impact force and standard deviation of centre of pressure (COP) were recorded during a single leg hop and hold. Subjects were also tested for training effects in strength (isokinetic and isoinertial) and power (vertical jump). Both methods increased neuromuscular power and control. The improvements in power following balance training suggests these high school athletes were of low training status and potentially limits the utility of these findings. This would suggest a novice effect whereby gains are made regardless of the training mode or dose. It may be concluded that these results demonstrate efficacy of plyometrics in a high school population. However the presence of a gain in strength and power means that it is remains unclear as to whether neuromuscular control was affected through enhanced skill or if this were aided by greater neuromuscular capacity.

The question of strength versus control was explored by Lephart et al. (2005) who compared plyometrics with resistance training. Knee and hip strength, landing mechanics, and muscle activity were assessed pre and post either a plyometric or resistance training programme. Surface EMG data was collected during a landing task with peak activation time and integrated sEMG of thigh and hip muscles measured. Strength scores improved following both training programmes without differences between groups. Similarly, glute medius preactivity increased for both groups during the landing task. The role of neuromuscular power should not be overlooked in enhancing mechanics. Indeed, discussing neuromuscular control and power may be something of a false dichotomy as a skilful athlete may utilise their capacity for force production more effectively but this must be accompanied by sufficient strength reserve to attenuate a forceful landing. Similarly, a high capacity for force production may not be utilised in the absence of sufficient control or preactivation through anticipation. This is illustrated in an evaluation of plyometric training by Baldon Ride et al. (2014) who demonstrated a decreased knee abduction and hip adduction in a hop test following 8 weeks of plyometric training. These biomechanical changes were accompanied by increased eccentric hip adductor and abductor torques. This does not prove that the two adaptations are linked but there is at least a logical hypothesis to support such an argument.   Furthermore the results demonstrate the capacity for plyometrics to improve control as well as strength in the hip and knee.

The discussion around neuromuscular capacity versus control may perhaps direct us toward consideration of the adaptations which may be gained from plyometric training. This is discussed in more detail below but it should be considered in the current context that plyometrics themselves represent a multi-faceted mode of exercise which incorporates balance, strength and power training. Hrysomailis (2007) concluded a review of balance training studies that, whilst not universally effective, balance training can contribute to reducing knee and ankle injuries, particularly in reducing re-injury. An awareness of this should be carried into plyometric programme design if reduced injury risk is a priority. The use of unilateral exercises as well as other balance challenges may increase the efficacy of a plyometric programme designed to reduce risk.

Little consideration within the literature has been given to the content of plyometric programmes used with an injury reduction focus, this absence is addressed in conclusion by a review of the literature by Yoo et al. (2010) who suggest that research should address identifying optimal protocols and intensities for injury risk reduction. Chappell and Limpisvasti (2008) used two differing methods to assess a mixed plyometric training programme. Drop jump and a stop jump assessments revealed differing biomechanical adaptations to the plyometric programme. Dynamic knee valgus moment decreased in the stop jump but not the drop jump whereas initial and maximal knee flexion angles changed in the drop jump but not the stop jump. These results would appear to illustrate the importance of task specificity which must be considered when designing a training intervention. This is supported further by an evaluation of glute and hamstring activation patterns across 5 different plyometric exercises (Struminger et al., 2013). Surface EMG was measured in 41 subjects across a range of common plyometric exercises. Results revealed differences in activation patterns in both the preparatory and landing phases of jumps in hamstrings and gluteals. This supports a view that exercises should be matched to the injury risk task. It may also be useful to adopt an approach of using a range of exercises for varied stimulus.

It is clear that injury risk is increased in landing tasks when biomechanics are sub-optimal and that plyometrics are an effective tool in addressing such risk through increases in neuromuscular power and control. Further research is required to explore the specific adaptations which underpin this and the identification of optimal protocols.

2.2.3 Adaptations to Plyometric Training

The elastic nature of the SSC would seemingly favour training adaptations towards compliant rather than stiffer tendons (Wilson et al., 1991). Whilst a compliant tendon would appear to be advantageous for SSC performance a number of studies have demonstrated improvements in jump performance alongside increases in tendon stiffness following plyometric training programmes (Foure et al., 2010, Foure et al., 2012, Burgess et al., 2007). Foure et al. (2012) found a trend towards increased stiffness of the Achillies tendon following 14-weeks of plyometric training. The absence of statistical significance may have

been partly as a result of the low statistical power of the study as only 9 subjects formed the experimental group. The assessment of tendon mechanical properties was also based on isometric measures which may not best reflect the nature of plyometric performance. However these did include an assessment of maximal rate of torque development in isometric plantar flexion. This may, to some extent, replicate the mechanical demands placed on the MTU to resist dorsi-flexion on ground contact although this is a somewhat tenuous association. The training sessions were reported to be based on 200-400 repetitions per session. This is a far higher volume than is generally recommended or can be tolerated by athletes (Potach and Chu, 2000). Consequently the intensity of training is likely to be very low in order to tolerate such volumes and may have been insufficient to elicit maximal tendon adaptation. Conversely such high volumes may have exceeded the capacity for tissue regeneration following training. The magnitude of increase in tendon stiffness following plyometric training reported by Foure et al. (2010) and Burgess et al. (2007) were similar (24.1% over 14 weeks and 29.4% over 6 weeks). The greater gains over a shorter period found by Burgess et al. (2007) are likely to be a result of the high intensity training protocol which utilised maximal single-legged drop jumps as the primary training exercise in comparison with the single-joint plantar flexion exercises used by Foure et al. (2010).

Kubo et al. (2007) used a 12-week training programme for the plantar flexors with subjects performing a plyometric training programme on one limb and a resistance training programme on the other. This resulted in an increase in tendon stiffness in the resistance trained limb. Plyometric training increased joint stiffness but not tendon stiffness and resulted in improved performance in a range of jump tests on a sledge apparatus which the resistance training did not. The absence of an increase in tendon stiffness may have been a result of the low loading used during the plyometric programme but sufficient detail is not provided to make cross-study comparisons. Both this study and the study by Burgess et al. (2007) have shown greater increases in tendon stiffness following resistance or isometric protocols over plyometric training. The greater contraction duration and time under tension associated with these methods is likely to be the determining factor in this difference as greater levels of mechanical strain will naturally be accumulated. This is known to be crucial in driving tendon adaptation (Arampatzis et al., 2010, Magnusson et al., 2008). These results demonstrate the importance of distinguishing between stiffness of the MTU and the tendon

itself. Furthermore, it would appear that the improvements in jump performance following plyometric training are the result of enhanced performance of the gross MTU despite adaptation to the tendon which in isolation may be regarded as having a negative effect. Changes in tendon qualities such as increased collagen synthesis which result in increased stiffness may also be advantageous when required to tolerate greater forces following a training effect on the MTU. These studies utilised training programmes lasting 6-14 weeks (Burgess et al., 2007, Kubo et al., 2007, Foure et al., 2010, Foure et al., 2012). Therefore the results can be considered to be reflective of the adaptations associated with short to medium term training interventions. Longer term training may require further investigation to evaluate any adaptive response within the tendon tissue.

As discussed previously, changes to the mechanical properties of the muscle tissue may contribute to increases in passive stiffness of the MTU (Foure et al., 2012) which Lindstedt et al. (2002) suggest may be through adaptations to titin filaments. There are a number of titin isoforms which vary in elasticity/stiffness. These correspond with the qualities seen at fascicle level. A study involving rat muscle fibres has shown a repeated bout effect whereby titin mRNA expression was not increased after an initial eccentric exercise bout but rose after a 5th bout (Lehti et al., 2007). Bellafiore et al. (2007) also found increases in titin expression following endurance running training in mice. The authors hypothesised that this adaptation was in response to the repeated SSC exposure and would enable greater use of elastic energy towards more efficient movement. Marcaluso el al. (2014) found disruption of titin filaments following plyometric exercise which resulted in a lengthening of the filaments which was still evident after 8-weeks of abstaining from training. This effect did not differ between the control group and the exercise group who performed 8-weeks of training. This would suggest that the disruption seen after a single session is not a mechanism responsible for a repeated-bout training effect seen with plyometrics. Lehti et al. (2009) did not find an increased in titin expression in humans following a bout of fatiguing jump exercise. The use of a single bout of exercise may have been insufficient to elicit the repeated bout effect seen in animal studies though. Degradation of titin following heavy eccentric exercise has been demonstrated (Trappe et al., 2002) although the demonstration of this effect and any subsequent adaptive response following plyometric exercise is yet to be demonstrated in human subjects.

The effect of plyometric training on muscle fibre type is currently unclear. Studies have demonstrated an increased percentage of Type II fibres following SSC exercise in rats (Almeida-Silveira et al., 1994, Markovic and Mikulic, 2010). However only a single study has found a similar effect in human subjects (Malisoux et al., 2006a). In contrast, Kryolainen et al. (2005) failed to demonstrate a change in muscle fibre distribution despite performance gains following training. A notable difference between these two studies is that the former took biopsies from vastus lateralis whereas the latter used gastrocnemius. It is possible that the muscle fibre adaptation is specific to the nature of the role of the associated muscle within a movement task.

Hypertrophy of muscle fibres is a well-established phenomenon following resistance training (Damas et al., 2015, Schoenfeld, 2010). However this effect has not been explored to the same extent following plyometric training. Of the few studies which have been conducted, Potteiger et al. (1999) found increases of around 5-7% in fibre size whereas another group in separate studies found gains in the region of 10-15% (Malisoux et al., 2006a) and 22-23% (Malisoux et al., 2006b). Clearly there is potential to augment performance following plyometric training through this mechanism. All three of these studies used 8-week training protocols over 24 sessions using similar exercises and volumes. Therefore the wide variance in difference is likely a result of the multi-factorial nature of hypertrophy and the influence of gentic potential for hypertrophy, nutrition and training history. The subjects in these studies were not experienced athletes and so it cannot be assumed that gains of the same magnitude, or at all, may be achieved in an athletic population.

Only one study has evaluated the effect of plyometric training on muscle architecture, which was combined with sprint training (Blazevich et al., 2003). When compared with subjects who performed resistance training protocols, the plyometric group demonstrated a decreased angle of pennation of vastus lateralis whereas the weight training group showed an increase. This is consistent with the greater contraction velocities associated with plyometric training and the subsequent advantage in achieving a greater number of sarcomeres in series. Further research is required to support this single study. However the

results may illustrate the influence of training status on adaptations as athletes engaged in resistance training may experience muscle architecture changes different to those who are not.

Another aspect of performance enhancement following plyometric training of interest is the possibility of improvements in contractile performance at muscle fibre level. Relatively few studies have evaluated this area. Grosset et al. (2009) found increases in peak torque (7.1%) and rate of torque development (10.8%) following 10-weeks of plyometric training. Testing was conducted using electrostimulation with torque measured via an ankle ergometer. The outputs reported are thus reflective of the MTU rather than specifically within the fascicles. Muscle biopsies of vastus lateralis were used by Malisoux et al. (2006b) to evaluate changes in performance within a single muscle fibre. Following 8-weeks of plyometric training subjects exhibited increased single-fibre diameter, PF, and shortening velocity, leading to enhanced fibre power. Notably, these adaptations were consistent across type I, IIa, and IIa/IIx fibres. This would suggest that similar outcomes could be expected regardless of an individual's muscle morphological make-up.

Away from considerations around performance enhancement, attention has also been given towards the potential for plyometric training to improve bone health in adolescents. Markovic and Mikulic (2010) reviewed 13 studies on this population, 12 of which found positive gains in bone mass (relative gains of 1-8%). These gains would appear to continue to augment bone development in the long term beyond normal development. Naturally the opportunity to increase bone mineral density is appealing to a pre and post-menopausal female population. Gains have been demonstrated in the pre- but not post-menopausal population (Bassey et al., 1998). The authors conclude that given that other forms of exercise such as resistance training and jogging have demonstrated improvements in bone mass in estrogen-deplete postmenopausal women, plyometric training may not represent an optimal stimulus towards this goal.

The importance of pre-activation of muscle prior to the initiation of a SSC has been discussed previously. Chimera et al. (2004) and Kyrölänen et al. (1991) demonstrated adapted motor strategies which produce earlier and larger pre-activation bursts following

plyometric training. The level of pre-activation appears to be based on the individual's perception of the task. Ishikawa and Komi (2004) found significant differences in the level of preactivity in vastus lateralis, medial gastrocnemius and soleus across 4 progressive drop jump heights. Therefore there appears to be both a chronic training effect towards greater levels of preactivity and an acute modulation of this motor strategy in response to the perception of the task. Ishikawa and Komi (2004) also found sEMG activity during the braking phase increasing with increasing drop jump heights. However this may simply have been a reflection of the increased preactivity and it is not clear whether a distinct increased neural drive in this phase occurred. This pattern of earlier and larger preactivity responses is potentially important not only in order to enable lengthening to take place primarily at the tendon but it also presents the possibility of a greater rate of force development (RFD) and, crucially, greater impulse. This is important as the brief ground contact times associated with plyometric exercise do not allow an individual the opportunity to reach maximal force. Beyond the preparatory phase, there also appears to be a general increased neural drive following training, as demonstrated by greater levels of sEMG in vastus lateralis during maximal isometric leg extension testing (Behrens et al., 2014, Behrens et al., 2015). However, caution should be exercised when interpreting sEMG following training exercise protocols and this may be the result of an increased central drive but may also be influenced by adaptive tissue changes within the muscle.

Nakata et al. (2010) provide interesting insight into the potential source of the adaptive neural responses following training through neuroscience. Reinforced neural networks and plastic changes in the brain can be induced by the acquisition and execution of compound motor skills during training that requires quick stimulus discrimination, decision making, and specific attention. Whilst the scale of contribution of such adaptation to performance improvements is unknown, it is clear that improvements in plyometric performance are not limited to muscles and tendons of the limbs involved.

Plyometrics are typically high velocity, multi-joint exercises which are inherently complex in nature. Consequently their execution is underpinned by high levels of motor skill. Computer simulation has shown that simply gaining strength in the musculature involved in jumping, without accompanying motor skill adaptations, may be insufficient to evoke a performance

gain (Bobbert and Van Soest, 1994). Further, changes in jump performance following training may result in a more efficient strategy for the utilisation of existing muscular strength rather than the acquisition of greater strength per se (Cormie et al., 2009, Cormie et al., 2010b). During CMJ performance, subjects demonstrated an ability to de-load more rapidly (thus inducing a greater velocity of pre-stretch) followed by an increase in muscle activity in the eccentric phase of jumping and a decrease in activity during the concentric phase. This is a logical shift as it allows greater utilisation of the elastic properties of the tendon because it relies on the more mechanically efficient eccentric component of the force-velocity curve. Utilising this strategy may depend on the athlete having an "eccentric strength reserve". This is was highlighted by a trend towards greater performance gains in stronger individuals (Cormie et al., 2010c). This is an important finding as it suggests that the performance enhancements expected from a plyometric programme may vary in magnitude according to the training status of the individual. In the current context, the greater potential for enhanced jump performance in the strength trained athlete is in contrast to the so-called "novice effect" whereby untrained individuals typically make greater gains from exercise interventions than highly trained subjects.

The importance of a skilful jump execution is further illustrated by Luhtanen and Komi (1978) in an evaluation of segmental contributions to a jump. Kinematic analysis of vertical jumping demonstrated that the efficient timing of these segmental contributions plays a significant role in the vertical velocity achieved. In contrast, following a biomechanical comparison of good and bad jumpers, Vanezis and Lees (2005) concluded that the main determinants of jump height were muscle strength characteristics rather than technique. However, this does not preclude the possibility of gains in performance being achieved through technical improvements. The training background of the subjects was homogenous and therefore it may be likely that technical proficiency was similar amongst the group. It is likely that a physically gifted, or well-trained athlete, will be expected to out jump their physical inferior. However when physical qualities are matched skill in execution becomes a determining factor. This is further emphasised by an investigation into the kinetic and temporal factors related to jump performance (Dowling and Vamos, 1993). This study compared force- and power-time curves during vertical jumping to produce 18 kinetic and temporal variables. Although partly attributed to high technical variability amongst subjects,

the best three-predictor model explained, comprising duration of positive impulse, duration of negative velocity and PF, only 66% of jump height variance. Furthermore, a number of subjects produced low jump heights despite generating high PF thus emphasising the need to consider the duration of force application as well as the peak values attained.

The specificity of motor adaptations is evident when comparing athletes from differing sporting backgrounds. Eloranta (2003) compared the muscle firing patterns of jumpers, swimmers and soccer players. The results revealed significant differences in the way in which each group performed. The jumpers executed the technique in a manner which would optimize MTU stiffness. In contrast, rather than the optimal proximo-distal firing sequence (Bobbert and van Soest, 2001), the swimmers tended to execute a more simultaneous model. The authors suggest that this reflects the postural and stiffness demands of swimming. The soccer players showed the closest example of the theoretical proximo-distal model. The variation in inter-muscular activation strategies seen in these contrasting examples illustrates the complexity of motor skill performance in an apparently simple plyometric task such as a CMJ. Masci et al. (2010) also demonstrated differing motor control patterns during landing between volleyball players and non-players, thus suggesting a task specific learning effect.

Whilst the skilful execution of movement towards an optimized technical model clearly represents an area of potential performance gain, the variation in technique to elicit differing physical outcomes is rarely discussed. Cappa and Behm (2013) found that simply changing the foot presentation between a fore foot or a flat foot landing had profound implications on kinetic variables and muscle activation patterns during drop jumping. Fore foot landings produced a quicker contact time (277±67 ms vs. 364±86 ms) and greater peak ground reaction forces (3633±946 N vs. 2693±525 N). Whilst there was variation across the 4 muscle groups assessed (rectus femoris, biceps femoris, tibialis anterior and gastrocnemius) the flat foot landing generally produced the highest levels of muscle activation. This highlights an inherent flaw in most of the plyometric literature in that exercises are discussed as being homogenous by definition. This important study demonstrates that all drop jumps are not created equally, even within an individual subject.

2.2.4 Population Differences.

Relatively little attention has been paid to the differences in performance and adaptation to plyometric exercise in different populations. This is perhaps reflected with the coaching training literature which makes little or no distinctions in plyometric prescription nor the potential for differing adaptation mechanisms and magnitudes across populations. The primary focus of cross population comparisons to date has been placed on training background.

A number of studies have highlighted differences in how people jump. Whilst it does not automatically follow that such differences will require an alternative prescription or result in altered adaptations an awareness of such differences and the potential implications is important. Eloranta (2003) compared the muscle coordination patterns of swimmers and track & field athletes via sEMG during CMJ and drop jumps. Track and field athletes performed according to the proximo-distal model described by Bobbert and van Soest (2001) and displayed a pattern of reciprocal inhibition between agonists and antagonists associated with efficient technique. Authors suggested that the patterns displayed in this group best reflect a stiffness innervation associated with effective elastic recoil of the MTU. In contrast, swimmers exhibited more of a simultaneous model of muscle contraction rather than proximo-distal. Swimmers also tended to co-contract antagonists and agonists of the thigh and shank rather than demonstrating reciprocal inhibition. Such a coordination pattern is consistent with the postural and stiffness demands of swimming and suggests an adaptation of the CNS to prolonged exposure to sport specific stimuli which impacts on non-related movement patterns. The stark differences seen across groups in this study could potentially have significant implications on the biomechanical stimulus of a plyometric training programme with the athletics model being consistent with optimal use of tendon recoil and the SSC and the swimmers potentially relying more on contractile force.

Evaluations of plyometric performance in power versus endurance athletes have also received attention within the literature. Kyrolainen and Komi (1995) compared power and endurance athletes during drop jumping. As would be expected, power athletes produced more power in each drop jump condition. However, analysis of muscle activation patterns

suggest that this superior performance may be the result of differing patterns of muscular activity rather than simply greater magnitude of work. Power athletes demonstrated a faster rate of preactivity prior to ground contact and a smoother muscle activation pattern during ground contact. As discussed previously, preactivity is a critical element of an effective SSC and plays a significant role in determining the opportunity to achieve mechanical stiffness and optimal tendon loading. Therefore this neuromuscular skill, most likely an adaptation to exposure to this type of training, may differentiate between the nature of force production and the capacity to make use of a SSC between groups.

Power and endurance athletes have also been compared during hopping by Hobara et al. (2008). Kinetic and kinematic data were used during in-place hopping at 1.5 Hz and 3.0 Hz to assess leg and joint stiffness. Surface EMG data were also collected from six leg muscles. The power groups demonstrated significantly greater leg stiffness at both hopping frequencies, at the knee at 1.5 Hz, and at the ankle at 3.0 Hz. Endurance athletes demonstrated significantly greater sEMG activity at both frequencies. These results suggest that power athletes are able to produce greater levels of leg stiffness through specific joint stiffness as a result of intrinsic qualities of the MTU rather than greater levels of muscle activation. The same group performed a similar protocol which compared endurance athletes with recreationally active subjects during hopping at 2.2 Hz (Hobara et al., 2010). A similar effect was seen with endurance athletes demonstrating greater leg stiffness as well as specifically at the ankle and knee. Combined, these two studies illustrate a pattern of greater joint stiffness, most likely through training exposure, with increased stiffness from recreational, to endurance to power athletes. Such findings not only illustrate the adaptations which may accompany these forms of training but highlight to coaches the altered performances which should be expected across groups.

Further evidence of differences in neuromuscular patterning have been shown by Avela et al. (2006) when comparing high jumpers with sprinters. These may typically be regarded as two relatively homogenous groups in that both represent power-based track and field events. However close analysis suggests there may still be important distinctions in jump performance. H-reflex and short latency reflex (M1) sensitivity were assessed during drop jumping. As exercises progressed a fatigue effect appeared to manifest in the sprinters

whereby both reflex peak-to-peak amplitudes showed a significant reduction towards the end of the exercise. This group also showed significant rises in serum creatine kinase 2 hours post-exercise. The authors hypothesise that the effects seen in the sprinters was a result of presynaptic inhibition as a result of muscle damage which was not evident in high jumpers due to a protective effect from high jump training. The finding of such differences between these similar populations highlights the need for further research across multiple populations.

2.2.5 Summary

Plyometric exercise is an effective tool for augmenting movements which utilise a SSC. This mode of training has been demonstrated to improve vertical jumping, sprint performance and running economy. These gains appear to be achieved through a number of contributory factors including increased MTU stiffness, increased tendon stiffness and neural adaptations, specifically enhanced preactivity and increased activity during the braking phase of the SSC. Furthermore, plyometric programmes may be used to reduce injury risk through adaptations in motor control. Further research is required to explore potential population differences in the performance of and adaptation to plyometric exercise. The focus of this review will now move towards the effective assessment of intensity and volume of this important exercise modality with a view towards enabling more precise prescription.

2.3 Quantifying Intensity in Plyometric Exercise

2.3.1 Overview

Plyometrics have consistently been demonstrated to be an effective tool for augmenting performance of movements involving a SSC. To date researchers and coaches alike have failed to determine a common method of quantifying the intensity of a bout of plyometric activity. This section will review the literature which has addressed this question and aim to provide direction to future research to advance the topic.

Despite being a commonplace feature in sports and rehabilitation programmes for around half a century, the accurate measurement of intensity during plyometric exercise has received relatively little attention within the literature. This is in contrast to other training methods such as resistance training and endurance training. In the former, simplistic but effective methods such as percentages of repetition maximums are complimented by monitoring tools such as the measurement of barbell velocity via linear encoders. Likewise, endurance training methods are supported by a raft of physiological indicators such as heart rate monitoring and blood lactate sampling which inform the programming process. Even the relatively complex training environment of team sports is now measurable through movement tracking systems such as GPS and accelerometer based systems.

In practice, plyometrics are typically measured on a simplistic scale according to the perceived level of impact (Ebben, 2007). The most common example of this can be seen in the adjustment of dropping height in the drop jump exercise. Such an approach can be viewed as defining intensity based on the task rather than the outcome. This may be appropriate in resistance training. For example, when lifting a given weight the task and the outcome are closely matched, particularly if the load is determined according to the maximal capabilities of the lifter. However, the task of dropping from a box and jumping maximally may result in a host of different outcomes according the technique used, the effort applied, the ability of the athlete, etc. This has been illustrated by Cappa and Behm (2013) who have shown that changing the ground contact position of the foot can result in

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dramatic differences in the forces produced during drop jumping and hurdle bounding. In such an instance, simply describing the drop height will clearly have failed to accurately and consistently described the imposed load.

Drop jumping appears to be a form of plyometric exercise which offers the most controllable conditions as the box height may be fixed and predetermined. However during this exercise it must be considered that there is margin for error as athlete may step down from, or jump from the box, thus affecting the actual drop height (Kibele, 1999). Further, there is also an assumption that linear increases in drop height represent linear increases in intensity. Velocity will naturally increase in a linear fashion but the response of the athlete may change based on perception of the task. Leukel et al. (2008b) demonstrated a reduction in the H-reflex when jumping from "excessive heights" (76 cm) in comparison with moderate heights (31 cm). The authors hypothesise that this may be a protective mechanism to reduce mechanical load on the MTU when an individual perceives the task to be unsafe. Under such conditions the increase in velocity achieved by using a greater falling height may not be translated into the expected linear increase in ground reaction force as reduced muscular activity will inevitably lead to greater yielding. Under such circumstances, impulse may still be accumulated via a greater duration of ground contact but with lower peak forces. The reverse of this effect may also be true if an individual increases their application to a jumping task as the perceived demands increase. Ishikawa and Komi (2004) demonstrated increased levels of sEMG activity in both the preactivity and braking phase of drop jumping across four progressive heights (actual drop height varied as percentages of maximal squat jump were used). Both of these studies illustrate the limitation of measuring plyometric exercise intensity based on the task alone. Furthermore, away from drop jumping, other plyometric activities present a greater challenge when attempting to judge the intensity based on the level of impact purely from the task description. For example, in repeated maximal vertical or horizontal jumps the effective "drop height" will vary between repetitions according to the performance of the previous effort.

The common protocol of describing a drop jump as a discrete action may be considered overly simplistic. Instead, whilst the respective components are related, it may be viewed as a number of interlinking actions, i.e. initial impact, deceleration, propulsion and subsequent

landing. These are illustrated in the force trace shown in Figure 2-1. This more detailed approach to describing the actions of an athlete enables a greater understanding of the biomechanical and physiological demands of the task.
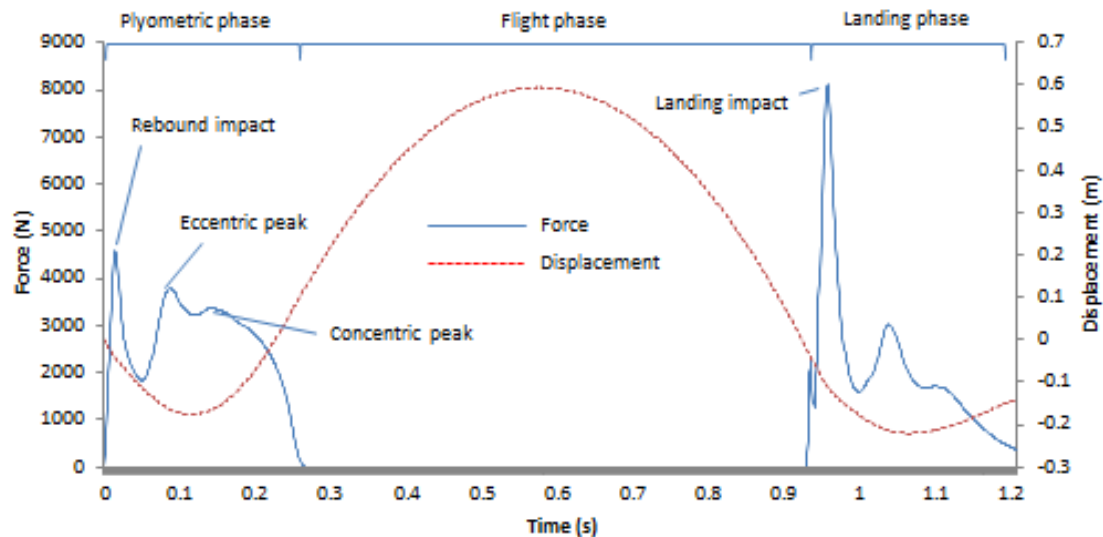
Figure 2-1 - Example of drop jump phases

2.3.2 Ground Reaction Forces

As the limitations of a task-descriptor based intensity scale become apparent, there has been a small but growing interest within the literature in intensity measures of plyometric exercise which are based upon the outcome of the effort. McNitt-Gray (1991) evaluated the kinematics and kinetics of drop landings in international gymnasts and recreational athletes using video footage and force platform assessment. Dropping heights of 0.32, 0.72, and 1.28 m provided a wide range of impact velocities (2.5, 3.75, and 5.0 m.s^{-1}) separated by equal increments in impact velocity (1.25 m.s^{-1}). Whilst the small subject numbers (n=6) did not result in statistically significant differences, a trend towards between group differences in peak impact forces was evident (gymnast PF 3.93±1.3, 6.26±1.9, 10.96±2.3 N.kg; recreational athletes 4.16±1.3, 6.38±1.7, 9.12±1.9 N.kg). This is likely to be influenced by strength and technical abilities as well as motivation of the subject. All subjects were instructed to use their preferred landing strategy. This is an interesting approach as it inherently leads to greater variability of technique and therefore kinetic data which describe varied actions. This is perhaps a realistic acknowledgement of the variability seen in

practical settings. This challenge to the reliability of the kinetic data is attenuated somewhat by the use of video to assess jump kinematics. This is an important aspect of plyometrics which is frequently ignored within the literature and is often essential in explaining changes in kinetic variables. The authors found that compared to the gymnasts, the recreational athletes exhibited lesser degrees of hip flexion during landings from low heights (gymnasts = 93.0±12°, recreational = 129±22°) and a greater degree of flexion when landing from the highest height (gymnasts = 61±16°, recreational = 49±13°). This is consistent with the kinetic data presented above which suggest a lesser degree of yielding in recreational athletes at the low height and a greater degree (as demonstrated by lower PF) at the highest height. Whilst this study only evaluates a landing task rather than a true plyometric exercise it clearly illustrates the potential for kinetic and kinematic data to add greater insight into the nature of an activity beyond the descriptor of the task itself.

Ebben et al. (1999) make a valiant attempt at exploring a number of possible methods for determining intensity in upper body plyometric exercises. This is a particularly challenging task as these exercises are complex in nature and do not automatically lend themselves to assessment via ground reaction forces. The paper discusses three possible methods of defining intensity and is perhaps best applauded for the exploratory and creative thinking and the stimulation of thought in the area rather than for any concrete conclusions reached. Although the topic under discussion is the broad category of upper body plyometrics, the paper deals exclusively with the medicine ball drop exercise. The first method under review proposes that optimal joint angles be determined at the elbow and shoulder during the amortisation phase. These would be based on sufficient load imposition to represent an adequate mechanical strain to elicit adaptation whist avoiding excessive joint angles which may represent suboptimal joint stiffness and elastic potential. This is rational in its assertions and is most likely the process which occurs in a subjective manner when coaches observe athletes performing the task. However, to apply such a method in a precise and scientific manner is fraught with potential error. The optimal joint angle will differ between individuals according to bone lengths, fascicle-tendon length ratio and strength qualities. The real-time accurate assessment of joint angles during training is also highly impractical. However, the consideration of kinematic rather than purely kinetic variables is an important element which should be taken from this work. A second concept discussed within the same

paper explores the possibility of basing upper body loadings on a percentage of the impacts achieved in lower body plyometrics. Given that optimal kinetic loadings for lower body plyometrics are yet to be identified this seems difficult to achieve. Further, this system proposes that a ratio is used to inform the percentage of lower body loading used in the upper body. Once again, this is subject to the significant individual variation in body shape and morphology.

Both of the methodologies above are explored but ultimately rejected by the authors for the reasons discussed. Instead, a system is proposed which seeks to induce a loading of 30% of one-repetition maximum (1RM) of a biomechanically similar resistance exercise. This is based on the theory that such a loading will elicit maximal muscle power outputs (Soriano et al., 2017). The authors produced a data table detailing a range of medicine ball weights and drop heights and the expected impact force which can be achieved with them, thus removing the need for regular monitoring of these forces in training. Therefore the only major practical limitation may be the need to have accurate 1RM data for the athlete. The system is also somewhat limited as it is either restricted to a single form of exercise or risks losing biomechanical similarity, therefore it is unlikely to be applicable to the bulk of a practical training programme. In terms of the philosophy behind this system, the assertion that maximal muscle power also represents the "optimal" training load is also open to question. Whilst this may represent the greatest mechanical output, it is not supported by data demonstrating that it will elicit the greatest training adaptation, which is of course the goal of any training regime. This study does not appear to provide a robust system of intensity measurement across a range of upper body plyometric exercises. However, it does provide a platform for debate and suggests some potential solutions which coaches and researchers may build upon. To date and to our knowledge, this remains the only study which focusses exclusively on systems to address upper body plyometric intensity.

Jensen and Ebben (2007) evaluated a range of kinetic variables in an attempt to explore novel methods of describing plyometric intensity. Six national level collegiate athletes performed a range of plyometric exercises on a force platform to measure peak ground reaction forces (PF) and eccentric rate of force development (E-RFD). Joint markers were also worn and video analysis used to estimate knee joint reaction forces (K-JRF). Despite

using a range of plyometric exercises, including some which used an augmented loading through the use of dumbbells, and a range of subject mass of 66-96 kg the authors failed to find statistically significant differences between PF in either absolute (N) or relative (N.kg) terms. This is in contrast to a number of other studies which have found PF to differentiate between plyometric exercises (McNitt-Gray, 1991, Wallace et al., 2010, Ebben et al., 2011, Wang and Peng, 2014). Relative PF ranged from 2.92±0.81 N.kg in a single-legged jump to 3.91±0.80 N.kg in a 61 cm drop jump. The failure to detect significant difference may be in part a result of the small subject group. The results may also be a reflection of subjects moderating technique to achieve a more homogenous self-selected intensity, although kinematic data is not provided to evaluate this.

Jensen and Ebben (2007) did detect significant differences across conditions in E-RFD. This is a compelling metric as plyometric exercises are characterised by the rapid production of large eccentric forces. E-RFD was defined as the first peak of GRF divided by the time from onset of landing force to the first peak of GRF. This point may be regarded as a landing impact spike rather than the eccentric phase which follows it and is arguably more reflective of plyometric performance. The results from this study also found a greater E-RFD in a CMJ (843 ± 357 N.s^{-1}) in comparison with a 46 cm drop jump (741 ± 347 N.s^{-1}). This is surprising given that the CMJ does not involve a landing phase. K-JRF also distinguished between exercises. E-RFD remains a compelling metric from a theoretical standpoint but further research is required to support its use as well as establishment of best practice in defining how such a metric is calculated in plyometric activities. Furthermore it may be necessary to establish a minimum threshold of force to avoid exercises which involve the rapid production of low absolute force levels being regarded as high intensity. Both K-JRF and E-RFD merit further evaluation although the processing of data associated with these methods may limit their practical usage. The utility of feedback during a training session often depends upon the speed with which it can be delivered to the athlete and coach in order to utilise the information immediately. This is not currently possible with variables such as K-JRF and E-RFD which take significant time to process.

Wallace et al. (2010) also quantified the kinetic demands of a series of plyometric exercises. In contrast to the exercise choices used by Jensen and Ebben (2007) these were restricted to

bilateral exercises thus making comparison easier. The authors used a simplistic measurement of PF only. As with Jensen and Ebben (2007), this was taken as the highest force recorded during the plyometric landing ground contact normalised relative to bodyweight. It should be noted that two of the five exercises used (CMJ and standing long jump) can be considered ballistic rather than plyometric as they do not involve a landing prior to the propulsion phase. Consequently the nature of the PF during the jumps is likely to be different, i.e. impact landing in plyometric movements and braking or concentric force in ballistic movements. Significant differences were found between exercises with a range of intensities demonstrated between 2.87±0.44 N.kg^{-1} (30cm drop jump) through to 5.39±1.64 N.kg^{-1} (90cm depth drop). The exercises used included a 30, 60 and 90 cm drop jump with each eliciting a progressively higher PF. A novel aspect of the author's approach was to recommend using CMJ as a reference index with plyometric loadings expressed as a multiple of this. This would potentially represent a practical method of comparing training intensities between exercises. The CMJ may not be well suited as the index measure though as this is essentially a movement dominated by muscular force production rather than elastic recoil (Bobbert et al., 1996a, Bobbert and Casius, 2005). Consequently prescription of training based on this index may result in disproportionate loads being performed by athletes depending on their concentric-eccentric strength profile. An alternative which is not discussed may be to use a low drop jump as an index measure. The authors suggest the findings may serve as a guide to practitioners to inform likely loadings during similar plyometric exercise. However they rightly urge caution given that factors such as age, gender and training status will likely affect the forces demonstrated. The findings may be more usefully regarded as a demonstration of the efficacy of PF as a means of differentiating between plyometric exercises in a manner which evaluates the resultant outcomes of a task rather than the task itself. Greater insight may be gained by evaluating the various phases of the force application, i.e. landing, braking, and propulsion. This would provide a greater insight into the nature of the training stimulus being delivered. Additionally, the joint-specific loading could also inform technical execution and exercise selection. PF should always be considered though as this represents the largest mechanical stress placed on the athlete which is perhaps a valid descriptor of plyometric intensity. It is important to be aware that this metric may be influenced considerably by the technique used by the athlete and joint angles and stiffness of landing will affect PF considerably.

However, whether such factors are viewed positively or negatively, PF remains the best quantification of the greatest level of stress placed on the athlete as a whole. This point-of-view also demands that the landing following a plyometric jump should be considered when assessing forces which the athlete must tolerate. This aspect of a jump is typically overlooked, particularly in ballistic exercises during which the landing may be significantly more stressful than the jump itself. Finally, PF also requires little processing of data and is therefore well suited to a practical training environment where force platform analysis is available.

Ebben et al. (2011) evaluated a broad range of kinetic variables across seven different plyometric exercises. Most academic enquiry has focussed on kinetic variables relating to impact such as PF and E-RFD. The authors included landing GRF and landing RFD but also measured variables relating to the concentric phase; take-off GRF, peak power and jump height. A number of significant differences were found across the exercises tested. Notably the ranking order of exercise intensity varied somewhat depending on the variable used. Broadly speaking this illustrates the fact that plyometric exercises vary according to the impact forces involved, contact times and propulsive effort. The authors suggest that practitioners may be better informed as to the most appropriate plyometric exercise to target a specific element of jump performance through use of this method. This is a valid point although perhaps these measures should not be confused with intensity. This approach is also potentially flawed as it assumes that the exercise descriptor, e.g. a drop jump or a bound, will hold a consistent execution both within and between athletes. Such an assumption ignores the potential for athletes to adapt technique according to their intent such as minimising ground contact or achieving maximum height. There is also potential for different athletes to adopt different styles of jump according to their own preferences, strength characteristics and anthropometry. Despite these limitations a similar approach was taken by Wong et al. (2012) who compared two lateral plyometric exercises in professional male soccer players. Comparison of lateral hopping and speed lateral footwork revealed the former to produce greater GRF and longer ground contact times, and therefore impulse, than the later. Again, such conclusions may be of limited value unless constraints are made to ensure that the exercises are executed to well-defined kinematic and kinetic

parameters. Ultimately these may be more important than the gross movement description of the exercise itself.

Sugisaki et al. (2013) expanded on the kinetic assessment of the athlete as a single entity and evaluated the relative contributions of hip, knee and ankle joint torque using inverse dynamics analysis. By combining kinetic and kinematic data in this way a clearer picture of the nature of the exercise intensity may be gained. The study compared two-foot ankle hop, rebound CMJ, double-leg hop, double-leg tuck jump, single-leg tuck jump, and depth jumps from a height of 30 cm and 60 cm. These results indicated that differing amounts of work were performed at each joint across the various exercises. Whilst mechanical output at the knee was relatively stable across exercises there was great variation at the ankle joint. Exercises which are typically considered low intensity due to the low GRF and rapid contact time such as two-foot ankle hops and the double and single legged tuck jumps produced the highest plantar flexion outputs (85±7, 89±5 and 105±6 J). Conversely drop jumps from 30 cm and 60 cm produced only 32±2 J and 51±5 J. This pattern is likely the result of the need to attenuate greater forces at the hip and knee during drop jumping in contrast with hopping exercises, thus off-loading demand on the ankle. These findings are consistent with the characteristics of these exercises and therefore it may be assumed that similar joint bias effects may be consistent across subjects groups. This will only remain the case if exercise technique is relatively homogenous though and therefore individual assessment may still be required. A key finding from this study was the mismatch between traditional intensity rankings of exercises as low, medium and high intensity and the joint specific loadings. This was replicated in a similar study by Van Lieshout et al. (2014) who calculated inverse dynamics across seven plyometric exercises. Summed peak power at hip, knee and ankle, normalised to body weight were compared with subjective intensity ratings of each exercise as described by Potach and Chu (2000). Results revealed a mismatch between subjective rankings of exercises and joint specific peak power absorption. When considered individually, neither hip, knee, nor ankle peak power absorption corresponded with subjective intensity ratings. Significant discrepancies still existed in some exercises when summations of the peak power absorption were considered across all three joints although these were fewer than when each joint was compared in isolation. This approach clearly provides a level of insight into the nature of mechanical loading induced by plyometric

exercises beyond traditional descriptors or gross measures of force. However the practical utility is somewhat limited by the time cost of processing such information as it cannot be applied in a practical setting. The findings may be used to inform practitioners as to suitable exercise choices depending on the targeted joints or musculature. However some degree of caution must be exercised as such recommendations are only valid given a degree of consistency of technique with that observed within tested subjects. An awareness of the need to consider individual joint loadings in exercise selection may be of particular use in a rehabilitation setting where there is a need to limit or target specific joint loadings.

2.3.3 Muscle Activation

The majority of enquiry regarding the quantification of plyometric intensity has focused on the mechanical loading imposed on the athlete. A novel approach was investigated by Ebben et al. (2008) who used sEMG to measure loading as represented by the level of muscular activity across a range of exercises via mean integrated sEMG. This is in contrast to the traditional approach of relying on kinetic variables to measure mechanical loading. Motor unit activation was assessed in rectus femoris (RF), biceps femoris (BF), and gastrocnemius (G). Despite high variability in the data, significant differences were found across a number of exercises in RF and G but not in BF. This is consistent with the view of RF and G and being chiefly involved as agonists in jumping activity whereas BF may be considered an antagonist. BF data were also reported as being highly varied according to athlete landing strategy which may have contributed to the absence of statistically significant differences. The most notable finding from this study was the conflict between previous intensity rankings of exercises based on GRF and the motor unit activation. Drop jumps from 31 cm and 61 cm were the lowest ranked exercises whereas ballistic exercises such as a CMJ and a jump on to a box were amongst the highest levels of motor unit recruitment in both RF and G. The authors hypothesise that this may be explained by a greater reliance on elastic sources of force production in those exercises which include the absorption of a landing. The stark contrast between GRF findings in previous studies and motor unit recruitment in the present study would suggest and inverse relationship between the two whereby increasing impact results in a reduction in contractile activity and a shift towards reliance on elastic energy. This may present practitioners with further insight

into the nature of the training stimulus being applied and the likely nature of adaptation which it may elicit. The findings also demonstrate the multifactorial nature of plyometric intensity. Just as it would appear that intensity rankings are not consistent across the hip, knee, and ankle, the mechanical loading and the motor unit recruitment are independent. Whilst this is an important finding, it should be noted that as with other methods previously discussed, the practical application of using sEMG in an applied training environment is highly limited.

In contrast to the findings of Ebben et al. (2008) progressive motor unit activation in RF was found by Peng et al. (2011) across drop jumps from 20 cm, 30 cm and 60 cm (20 cm=82.3±30.8 %MVC, 30 cm=88.9±38.9 %MVC, 60 cm=107.0±45.9 %MVC). The failure to normalise sEMG activity by Ebben et al. (2008) is a major weakness in the methodology and may contribute to the difference in findings. Although increasing drop height may result in a greater reliance on elastic sources this must be matched by increasing levels of muscular force in order to ensure that lengthening occurs within the tendon rather than the fascicles (Ishikawa and Komi, 2004). This does not remove the possibility that the intensity of low impact plyometric exercises involving high levels of motor unit activation may be underestimated by GRF assessment alone. However the suggestion of reducing muscular activity with increased impact requires further investigation. In keeping with previous discussion regarding technique, it may be overly simplistic to consider increasing drop height as an isolated variable. If the change in height is accompanied by self-selected technique alterations by the athlete these may be partly or wholly responsible for changes in muscle activation patterns rather than the increased kinetic demand per se.

The importance of evaluating kinematic variables to provide context to kinetic assessment has been discussed previously within this chapter. This view is supported further by Cappa and Behm (2013) who combined GRF and sEMG assessment with specific technical instructions. Subjects performed hurdle jumps and drop jumps with both forefoot and flat foot landings. Flat foot landings resulted in longer ground contact times (26%) with significantly higher RF sEMG activity (47%) in comparison with forefoot landings which induced a much greater concentric RFD (45%). Kinematic data to evaluate the consequence of these cues on hip and knee mechanics was not collected and therefore a broader picture

of the wider implications on jump execution is not clear. Overall these findings support the notion that the contribution of neuromuscular and elastic force production varies according to kinematic variables. It also highlights an inherent weakness in the literature that small differences in kinematics (i.e. foot contact) may significantly affect the nature of an exercise and therefore broad definitions such as "drop jump" may not be suitable descriptors upon which to base assumptions of homogeneity. The accompaniment of kinematic descriptors should be considered best practice in order to allow interpretation of kinetic data and motor unit recruitment.

2.3.4   Summary

Intensity in plyometrics has been defined as the amount of stress placed on the muscles, joints, and connective tissues involved in the movement (Potach and Chu, 2000). Consequently it seems reasonable to assert that the mechanical stress placed on the body should be considered as part of any assessment of intensity. At a minimum this should describe the greatest level of force experienced during a movement. PF represents such a metric and appears to distinguish between exercises. Other kinetic variables which have also been found to distinguish between plyometric exercises and may be considered representative of intensity include K-JRF and E-RFD. However, both of these require significant processing of ground reaction force data and therefore their practical utility maybe somewhat limited. To date the literature has not addressed the challenge of comparing forces in unilateral versus bilateral plyometric tasks. It is also clear that in order to achieve a more complete picture of exercise intensity the nature of force should be considered, i.e. impact, eccentric or concentric. Further research is required to explore the magnitude of difference between populations in order to inform exercise guidelines with particular emphasis on elite vs. non-elite comparison. Finally, further research is required to evaluate the efficacy of performance metrics such as E-RFD which relate specifically to the demands of plyometric exercise.

Whilst kinetic data alone may describe intensity, kinematic evaluation is required in order to understand the nature of this force and any changes between performances. In a research setting this may mean biomechanical measurement whereas in a practical setting a close

attention to technique may be more appropriate. A combination of kinetic and kinematic data may be used to evaluate specific joint loadings. Loading at a single joint may not match the gross descriptor of the exercise intensity and therefore this may inform prescription during rehabilitation where there is a focus on a specific joint or a performance enhancement setting with highly targeted biomechanical outcomes. Current research suggests loadings on the ankle and whole body may be commonly mismatched within current guidelines. Further research is required to confirm this and to assess the variability of technical execution across populations.

The level of neuromuscular activity during an exercise can differ significantly depending on the characteristics of the exercise technique. These can be modulated within the broad descriptor of an exercise, such as drop jump, based on variances in the technique self-selected by an athlete and the coaching instructions provided to them. Therefore exercise classifications cannot be assumed to accurately predict motor activity. The use of sEMG in a training environment is not practical and therefore practitioners need to develop an understanding of the biomechanical factors, such as foot position, which will influence motor unit activity. Current research is equivocal in this area and therefore further investigation is required in order to establish clear patterns within exercise progressions and adaptations.

It is noteworthy that within the literature, whilst there has been much focus on quantifying plyometric intensity, consideration of measurement of plyometric volume is essentially absent. This is perhaps a reflection of the common practice of counting ground contacts rather than differentiating between them. This may be considered a major omission within the literature, the investigation of which may potentially add significantly to the insight provided to coaches and athletes when evaluating the volume-load imposed during plyometric exercise.

This review will conclude with a discussion on the broader biomechanical assessment of effective jump performance which may inform coaching interventions when seeking to enhance performance.

2.4 The Kinetics and Kinematics of Effective Jump Performance

2.4.1 Overview

Historically within the literature the focus has primarily been placed on peak values when assessing jump performance through ground reaction forces. Recently a more in depth level of analysis has provided the opportunity for an alternative approach which considers the pattern of kinetic and kinematic characteristics rather than simply the peak values. The following section will provide an overview of this novel research and propose potential future directions of enquiry.

Ground reaction force data has been used to provide a kinetic description of CMJ performance both within research and applied practice. This has typically focussed on peak values, such as jump height, peak power and PF without consideration as to the way in which these variables are distributed about the movement. The CMJ holds significance beyond the specific performance of the task itself. The demands of the CMJ relate to many sporting scenarios where there is a need to express force rapidly such as jumping and sprinting (Hennessy and Kilty, 2001, Markstrom and Olsson, 2013). An "effective" jump may be characterised as one whereby the desired outcome, be that the greatest possible jump height, the briefest contact time, or a combination of these, is achieved to the greatest extent possible for the given force applied. The dual aims of maximising jump height and minimising contact time often act in opposition within the timeframes experienced in sporting contexts as extending the contact time offers the potential to generate greater impulse and resultant jump height. However, sporting scenarios commonly demand that an athlete achieve the greatest possible height under significant time constraints.

Recently the use of temporal phase analysis (TPA) has provided greater insight into the way in which jump height has been achieved (Cormie et al., 2009, Cormie et al., 2008, Cormie et al., 2010b, Gathercole et al., 2015a, Gathercole et al., 2015c). An example TPA force- and velocity-time curve from a CMJ is presented in Figure 2-2 with movement time displayed in relative terms following the TPA.
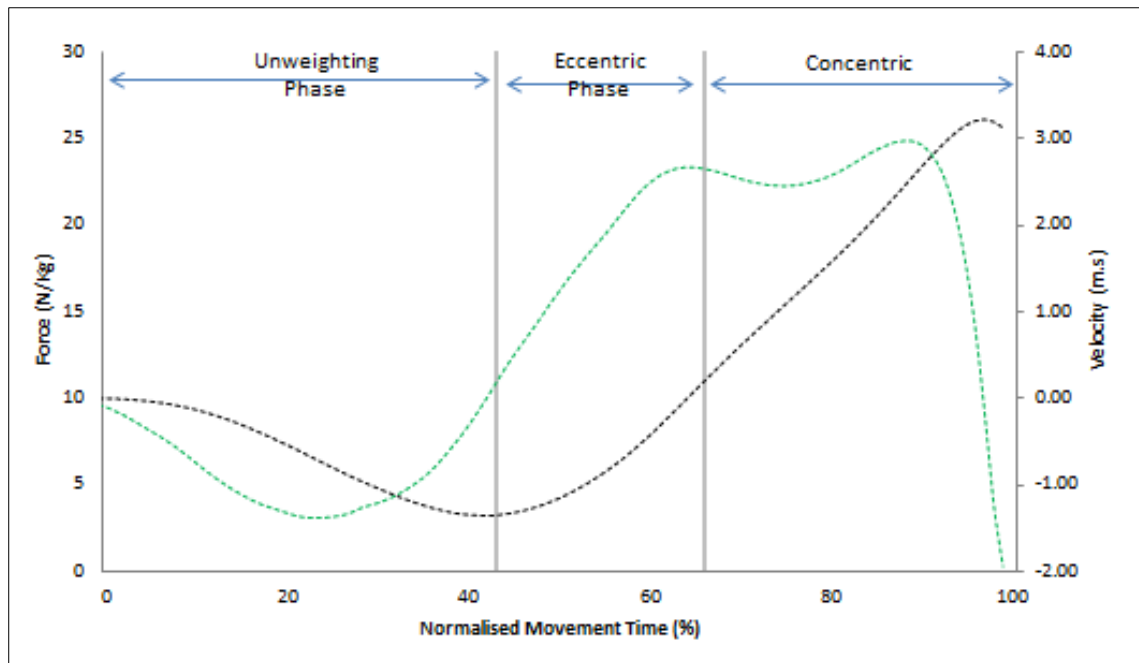
Figure 2-2 - Example CMJ Force-, Velocity-Time Curve using TPA

Cormie et al. (2008) were the first to utilise such a TPA approach during an investigation which compared jump squat performances across 5 external loading conditions from 0-80 kg. The TPA enabled all jumps to be compared over 500 samples regardless of the actual movement duration. Originally sampled at a rate of 1000 Hz, force-, velocity-, displacement- and power-time curves were selected from the initiation of the eccentric phase to the point where each variable equalled zero. The displacement-time curve ended at the point of maximum displacement. The number of samples in each individual curve was then modified to equal 500 samples by changing the time delta between samples and resampling the data. A consequence of this approach was that in heavier loaded jump squats, which took place over a longer time frame than lighter loaded jumps, the sampling frequency differed dramatically (force curves sampled at a modified frequency of 502 Hz at 0 kg vs 318 Hz at 80 kg). This represents a potential limitation of the methodology, particularly when comparing across exercise tasks of differing durations. When used to compare CMJs this issue is largely mitigated provided that additional and varied external loadings are not introduced. The value of the TPA is demonstrated in comparisons between 0 kg and 20 kg loadings during which peak power values were not significantly different but the 0 kg condition elicited higher power outputs during 34% of the movement. When evaluating phases of the jumps, significant differences were demonstrated in the unweighting (16.8–29.4%), braking (54.8–

68.6%), and propulsion (81.2–88.4%) phases, thus illustrating the merit of considering metrics beyond peak values. Whilst it was not the primary question under investigation, this approach demonstrated the potential to gain greater insight into the biomechanical mechanisms involved in improving power output during jumping through TPA.

Having established an additional level of insight into CMJ performance through TPA, Cormie et al. (2009) conducted both a cross-sectional and longitudinal comparison of experienced jumpers (CMJ >0.5 m) with non-jumpers (CMJ <0.5 m). The cross-sectional comparison found that experienced jumpers achieved superior jump performances which were attributed by the authors to physiological superiority as represented by the greater strength levels. Significant differences were observed in peak values of power, force, velocity and displacement. The TPA revealed that the jumpers achieved significantly greater values within the propulsion phase in the power-time (90-99%), force-time (95-98%), velocity-time (85-92%) and displacement-time (85-100%) curves. The longitudinal comparison involved subjects being assigned to a training (12 weeks of power training) or control group. Following the training period subjects exhibited altered CMJ mechanics characterised by a greater depth of descent. Notably this was achieved without increasing the duration of the eccentric phase and consequently eccentric power, force and velocity were all greater following training. This increased emphasis on the eccentric phase altered the shape of the force-time curve which saw the establishment of a bimodal force tracing with an enhanced eccentric peak followed by a drop in force and a subsequent concentric peak. It is notable that this change in force application patterns following the training intervention was not evident in the cross-sectional comparison. This suggests that jump training leads to a superior strategy for the application of force during jumping, likely underpinned by enhanced strength qualities, rather than simply applying a consistent strategy with augmented strength qualities. Therefore the mechanism underpinning the enhanced performance following training appears distinct from that which distinguished the groups in the cross-sectional analysis.

This line of enquiry was continued by Cormie et al. (2010b) who utilised a TPA analysis to compare the effects of strength and power training on CMJ performance. This study also observed changes in the pattern of force application characterised by changes in the

eccentric contribution to jump performance. 32 subjects performed either a strength training programme (consisting of back squats at 75-90% 1RM) or a power training programme (consisting of jump squats at 0-30% 1RM), 3 times per week for 10 weeks. Both protocols resulted in significant increases in jump height, peak eccentric power, peak eccentric force, and peak eccentric-RFD during CMJ performance. Furthermore, these increases were significantly correlated with improvements in concentric performance (peak eccentric and concentric power, r=-0.71; peak eccentric and concentric force, r=0.89; peak eccentric and total RFD, r=-0.92). Critically, whilst concentric performance was enhanced in SSC movements (i.e. jumping), no improvements were seen in a concentric only movement (i.e. static start jump). These associations suggest that enhanced concentric performance is driven by an altered and superior strategy to utilise the eccentric phase of jumping. This fits the model of the SSC with a more rapid and forceful eccentric loading offering greater opportunity for elastic recoil (via SEC and PEC) and potentiation of the muscle spindle (Turner, 2010). The augmented force production during the eccentric phase was achieved in the absence of any changes to the depth of descent. Instead, greater levels of lower body stiffness (pre=3871±880 N.m^{-1}, post=7318±3066 N.m^{-1}) underpinned the enhanced eccentric phase, and subsequent improvements, during which mean and average eccentric force was greater, as was eccentric RFD.

TPA has been used in an alternative line of enquiry by Gathercole el al. (2015a) when evaluating the efficacy of the CMJ as a means of quantifying neuromuscular fatigue. This study employed the same TPA methodology as in previously discussed studies. CMJ testing was performed pre- and post- an intermittent endurance protocol designed to induce fatigue. Fatigue analysis compared the efficacy of "typical" variables, made up of peak measures of force, power and velocity throughout the total movement and mean measures of force and power through the concentric phase, with "alternative" variables generated by the TPA (force at zero velocity, area under the force–velocity curve, eccentric duration, concentric duration, total duration and mean eccentric and concentric power over time). Neuromuscular assessment via CMJ occurred at 0, 24 and 72 hours post the fatigue protocol. At 72 hrs, whilst jump height and peak power had returned to baseline the ALT variables revealed a longer duration of concentric and eccentric phases and total duration thus suggesting the adoption of an alternative neuromuscular strategy. In the context of

sports performance where task time constraints are often critical this may be considered sub-optimal. Under such conditions the consideration of phase and total duration of jump performance may distinguish between optimal and sub-optimal jump performance despite execution being consistent in terms of output (i.e. peak power and jump height).

Recently, McMahon et al. (2016) compared senior male rugby players (n=20, age=26±3.2 years) with their academy counterparts (n=14, age=19±1.3 years). Each subject performed 3 CMJ trials on a force platform recording at 1000 Hz. The analysis of these trials included a modified version of the reactive strength index (RSI-mod). This is calculated as the ratio of jump height to movement time rather than ground contact time as is used within a traditional reactive strength index. As hypothesised, senior players achieved superior jump height to academy players as well as greater reactive strength ability (jump height = 0.36±0.05 m. vs. 0.32±0.05 m, d=0.91, p=0.005; RSI-mod = 0.45±0.07 vs. 0.40±0.10, d=0.58, p=0.027). This was underpinned by meaningfully greater relative eccentric impulse (senior =1.4±0.2 $N.kg^{-1}.s$ vs. academy=1.2±02 $N.kg^{-1}.s$, d=0.58, p=0.065) and by greater relative concentric impulse (senior =2.6±0.2 $N.kg^{-1}.s$ vs. academy=2.4±02 $N.kg^{-1}.s$, d=0.86, p=0.004). Contrary to the findings of Cormie et al. (2009), the superior performance was not accompanied by significantly greater peak eccentric force (senior =24±3.3 $N.kg^{-1}$. vs. academy=22.7±2.5 $N.kg^{-1}$, d=0.43, p=0.220). There were also no significant differences in either relative eccentric or concentric force during the TPA. As a consequence these findings would suggest that within these two groups CMJ performance is distinguished by the movement strategy and physical capacity to produce greater impulse throughout the movement as opposed to a strategy which places greater emphasis on eccentric loading prior to the concentric phase. It should be noted that a visual inspection of the force traces suggested a more pronounced bimodal force trace in the senior group but this did not result in statistically significant observations.

The practice of using TPA to compare jump characteristics between groups has been extended to sex comparisons by McMahon et al. (2017a). Male rugby players (n=14) and female netball players (n=14) performed CMJ measured at 1000 Hz with a TPA performed as described previously. As expected, men jumped higher (M=32.1±5.1 cm, F=24.3±4.7 cm). No significant differences were observed in either the relative PF nor the force-time signatures of the two groups. However an alternative movement pattern was observed characterised

by a greater depth of descent during the eccentric phase by the men. The authors categorise the female strategy of a smaller depth of descent as relying more on leg stiffness. However it is not clear whether, or to what extent, the differences in depth of descent may have been influenced by anthropometry. Despite this limitation, leg stiffness was higher in females than males (M=96.3±33.9 N.kg.m^{-1}, F=142.9±83.2 N.kg.m^{-1}, p=0.06, g=0.71) thus supporting the theory of an alternative strategy used by female jumpers. An explanation for the alternative strategies used by the two groups is not presented. This requires further exploration although it could be considered that, as was observed by Cormie et al. (2010c), greater leg strength of the male athletes facilitated a greater depth of descent, although leg strength was not measured. This could be a product of gender or sporting background and it is not clear which of these factors contributes most to the differences in results.

An alternative approach to athlete groupings was taken by Sole et al. (2017) who measured CMJ height in 150 collegiate athletes (75 male, 75 female). Subjects were ranked by jump height and the top, middle and bottom 15 jumpers of each sex were taken forward for further analysis. Comparisons indicated that higher jumpers exhibited larger relative force and impulse during the concentric phase of the CMJ. These same characteristics also distinguished between sexes and reflected the greater jump heights of males compared with females. This study demonstrates the value of comparing force application patterns across groups to gain insight into the most effective strategies. The results of this study may be considered somewhat unsurprising with the predominant finding being a greater application of force during the concentric phase being predictive of performance.

Athletes have also been grouped according to jumping ability by McMahon et al. (2017b) although in this instance jumpers were classified according to RSI-mod score rather than jump height. Superior jumpers achieved higher jump heights and utilised a shorter movement time which resulted in a taller, thinner, active impulse. This appears to be underpinned by a more rapid unweighting phase which the authors hypothesise enabled greater loading of the SSC to achieve increased muscle spindle stimulation and elastic energy storage which subsequently augmented the concentric phase of movement. Such a technique must be supported by sufficient ability to produce braking force to counter the rapid unweighting, this was evidenced by increased peak eccentric power (high=20.59±5.07 W.kg^{-1}, low=14.58±3.63 W.kg^{-1}, p<0.001, d=1.36) and peak eccentric force (high=25.55±2.39

N.kg^{-1}, low=21.69±2.19 N.kg^{-1}, p<0.001, d=1.69). To an extent this mirrors the findings of previous studies which have demonstrated the importance of emphasising the eccentric phase of a CMJ. However the mechanism within this study is notable in that superior jumpers did not utilise a greater depth of displacement. Such a strategy is unlikely to be effective if seeking to minimise movement time as required when achieving a high RSI-mod score.

In a departure from the typical approach of grouping subjects by training background or jumping ability, Rice et al. (2017) adopted a novel approach whereby subjects were matched according to relative strength levels as assessed by 1-repetition maximum back squat normalised to body weight. Such an approach is appealing as it attempts to remove one of the key physiological determinants of jump performance, i.e. the ability to produce force, from comparisons. Consequently this may allow for a greater distinction between force application strategies rather than simply the capacity to generate force rapidly. The study compared jump characteristics across sexes to explore whether differences existed in force application when strength advantage was removed. Males jumped significantly higher than females, displaying significantly greater relative eccentric impulse (and therefore greater potential for use of elastic energy and active state preceding the concentric phase) and greater relative concentric peak power than females. Force magnitude and impulse during the concentric phase was greater in males than females but not significantly when analysed relative to body weight. These findings further support those of Cormie et al. (2009) who describe a model of optimal jump performance characterised by an augmented eccentric phase which enables greater power generation during the concentric phase. Whilst it is not clear why males may adopt such a strategy over females in the absence of a strength advantage the results provide further support for the need to assess the kinetic characteristics of jumping, including the force-, velocity- and displacement-time curves, beyond simply peak values.

2.4.2   Summary

The value of TPA to provide a more sensitive and insightful level of analysis than peak values alone has been established across a number of studies. This has been applied to a number of enquiries. TPA has illustrated changes in the kinetic characteristics of jumping

performance may change following fatigue despite the outcome of jump height remaining constant. The methodology has also provided valuable insight into the means by which people jump effectively, namely through a model whereby genetic advantage appears to be expressed as greater concentric force whereas training may lead to a more effective strategy which is characterised by an augmented eccentric phase.

The establishment of TPA as a methodology has led to a series of inquiries which have contrasted differing populations, including male vs. female and senior vs. academy, to increase understanding of the means by which heterogenous groups achieve performance. Further research is required to understand the optimal model which underpins the most effective jumpers. The concept of differing means of augmenting performance according to physiological superiority versus training effects requires further investigation. Finally, to date the TPA method has only been applied to ballistic challenges through the CMJ. An exploration of the potential to gain novel insight into the performance of plyometric exercises is still required.

2.4.3 Understanding Stiffness

The term "stiffness" is commonly used in applied practice and within both coaching and research literature. However, what exactly the term is referring to is often not clearly defined and can therefore be left open to interpretation and misunderstanding. This brief section will explore the various contexts in which the term may be used with regard to jump training.

Mechanical stiffness has been described as, "…the resistance of an object or body to change in length." (Brughelli and Cronin, 2008). In the context of jump training, this is typically used to describe the ability of an athlete to resist yielding to vertical force such as during the impact of a plyometric ground contact. This is most commonly calculated through the use of ground reaction force data collected via a force platform although the use of video footage is also both commonplace and useful. Mechanical stiffness can be calculated in a number of ways, the most common of which is illustrated below (McMahon and Cheng, 1990):

$$K_{vert}=F_{max}/\Delta y$$

K_{vert} = vertical stiffness; F_{max} = maximum vertical force; Δy= maximum vertical displacement of centre of mass

By considering the change in displacement of centre of mass, such an approach regards the athlete as a system rather than measuring the changes within various components of the system, e.g. at various joints. This system approach is described as vertical stiffness and provides a useful overall illustration of how well an athlete has coped with the imposition of force.

Leg stiffness provides a more discrete assessment of stiffness and is often used during biomechanical assessment of running. Leg length is considered from the centre of mass to the end of the leg and measured during the stance phase of running. This is very similar to vertical stiffness but may be useful for differentiating between changes in centre of mass displacement arising from yielding at the hip, knee and ankle versus movement of the trunk which may occur during jump exercises.

Finally, mechanical stiffness may be assessed as joint stiffness. As the name suggests, this provides an assessment of the resistance to changes in angle at specific joints and is calculated as the ratio of joint moment to angular joint displacement. The insight provided by calculation of joint stiffness can be valuable for those wishing to gain a deeper understanding of the factors affecting athletic movement. Understanding of the role of specific joints within human movement patterns may be enhanced by evaluating the stiffness requirements at a joint level. An example of such is provided by the findings of Farley and Morgenroth (1999) who reported ankle stiffness to be the key regulator of leg stiffness. On an individual athlete level joint stiffness may also be used evaluate stiffness at a given joint and thus direct training interventions towards either increasing or decreasing stiffness.

Much of the confusion around the term "stiffness" arises from a misunderstanding of the difference between the various forms of mechanical stiffness and the passive stiffness qualities of the tendon and muscle tissue. These are related to, but independent from, mechanical stiffness. The stiffness qualities of these tissues and their contribution to

effective use of elastic energy in SSC activity is discussed in section 2.1.3. The achievement of high levels of mechanical stiffness in plyometrics is primarily underpinned by a combination of the capacity of an athlete to produce a skilfully timed, high level of isometric force within the fascicles prior to and during ground contact, coupled with the intrinsic qualities of the tendon (Aura and Komi, 1986, Cronin et al., 2011). Changes in stiffness have been associated with changes in electromechanical delay (EMD) which may increase or decrease depending on the type of training employed (Grosset et al., 2009).

It would appear that there is an optimal level of stiffness which balances the potential for performance enhancement with injury risk. Such a level will be determined by the nature of the given activity and the physical make-up of the athlete themselves. With regard to injury risk, broadly speaking, a lack of stiffness may increase the risk of soft-tissue injury whereas excessive stiffness may increase the risk of bony injury (Butler et al., 2003). The level of stiffness required for optimal performance will vary according to the task and the role of the particular joint within that task. This is illustrated in an investigation into the stiffness requirements of the Achilles tendon by Lichtwark and Wilson (2007). This modelling simulation concluded that a compliant Achilles tendon was required for efficient locomotion (walking and running).

2.5 Summary

The SSC is a well-understood phenomenon which plays a significant role in human movement. The SSC is almost ubiquitous in human locomotion and the mechanism has the potential to increase the efficiency of prolonged endurance activities as well as augmenting short-duration explosive activity. Further, the magnitude of the SSC contribution to force production has been demonstrated to be considerable. As a consequence, understanding of the SCC and methods to enhance movements which utilise a SSC are of key consideration to those involved in enhancing human athletic performance.

Jumping exercises (plyometrics and ballistics) have been demonstrated as being an effective tool for enhancing a number of athletic qualities including sprinting, jumping and running economy. The measurement of prescription and analysis of these exercises has lagged behind other modes of exercise for several decades which have seen little advancement beyond subjective measures of intensity and simplistic analysis of performance based on jump heights. Whilst a number of studies have explored methods of quantifying intensity in plyometric exercise a consensus remains elusive. In the absence of an agreed methodology for accurate quantification of intensity the demands of plyometrics on athletic populations is poorly described and understood. The first two studies within this thesis will seek to address these issues. The first study will compare a number of means of measuring plyometric intensity in order to identify that which is most valid, reliable and of practical use. This methodology will then be applied in practice within the second study to compare the intensities of popular plyometric exercises in an elite athletic population. In doing so it is intended that the value of the methodology will be demonstrated whilst also providing a valuable insight into the demands of plyometric exercise on this group.

Having established the need for a greater ability to quantify jump exercise, there is an emerging need to further understand jump performance from a qualitative perspective. In recent years the use of TPA as a tool to evaluate CMJ performance has illustrated that superior performance may be achieved through the deployment of alternative kinetic strategies as opposed to simply increasing the magnitude of force expressed. Further

research is required to explore these mechanisms and the third study in this thesis will, for the first time, compare across three athletic populations. Elite jump athletes will be compared with professional rugby players and recreational athletes with the aim of identifying key points of difference in the way in which differing levels of performance are achieved. Finally, the last study within the thesis will make a novel application of TPA in the context of a plyometric exercise. The drop jump will be used within an elite athlete group with comparisons made between the most and least effective jumps.

The overarching aim of this thesis is to apply contemporary and novel methods of biomechanical assessment to plyometric and biomechanical exercise. By doing so it is intended that greater insight will be gained into the quantification of volume and intensity of these forms of exercise and the biomechanical characteristics which underpin performance. Furthermore, the use of elite athlete populations within the thesis provides additional insight into the nature of excellence in jump performance to aid practitioners and researchers alike.

Chapter 3 – Evaluation of Plyometric and Ballistic Exercise Intensity and Volume.

3.1 Overview

Within the literature and in practice there is an absence of consensus as to the optimal means of describing intensity and volume in plyometric and ballistic exercises. This study will compare a number of approaches which have been deployed historically in search of a methodology which is sensitive and reliable and holds the greatest utility to those involved in the prescription of jumping exercises.

3.2 Abstract

The purpose of this study was to investigate the efficacy of ground reaction force data and electromyography to quantify intensity and volume in jumping exercises. Seven recreationally active subjects performed seven jumping exercises comprising bilateral, unilateral, plyometric (i.e. those jumps involving a rebound movement) and ballistic (non-rebound) challenges. Muscle activation in vastus lateralis (VL) and biceps femoris (BF) was measured using sEMG whilst ground reaction force data were collected using a force platform. Force and sEMG variables all showed high reliability (ICC>0.80) with the exception of VL during drop jumping. Statistically significant large effect sizes were observed for PF (0.7), peak eccentric power (0.8), and impulse (0.9) and small to moderate for sEMG variables (0.06-0.41). These results demonstrated that muscle activation only differed when comparing the eccentric phases of plyometric versus ballistic exercises with plyometric exercises inducing levels of activation approximately 2-fold that of ballistic exercises. Force variables proved highly reliability and sensitivity to describe intensity. Peak force and peak eccentric power provided valid and reliable measures of intensity in plyometric exercise. Bilateral plyometric exercises produced the greatest PF whereas bilateral ballistic and unilateral plyometric exercises produced similar PF. Impulse may be best considered as a measure of volume and may be used alongside PF to give a broader view of training volume-load than traditional measures (i.e. number of ground contacts). The ranking order of exercises by impulse followed the same pattern as described for intensity via PF. Surface EMG data revealed significant differences between ballistic and plyometric exercises but not

between exercises within these classifications. Furthermore, differences were only evident within the eccentric phase of movement. Therefore it was concluded that the monitoring of intensity via muscle activation is not supported but that the classification of exercises as plyometric or ballistic is sufficient to distinguish between the differences observed during the eccentric phase.

3.3 Introduction

During Chapter 2, it has been demonstrated that jumping exercises, comprising plyometric and ballistic exercises, have become established as a valuable element of training towards the enhancement of athletic performance.

The growing influence of sports science and organised training has increased the need to quantify training variables such as volume and intensity. The volume of plyometric exercise is commonly monitored by counting of repetitions (usually referred to as foot contacts for lower body plyometric exercises). This may be considered overly simplistic as the duration of contact is not considered. The intensity of these exercises is poorly defined, both empirically and within the literature. Traditionally, basic measures such as the drop height of a depth jump have been used, however this may be misleading as the task outcomes (i.e. resulting jump height, ground contact time and joint kinematics are not uniform for a given exercise and are variable based on potentially subtle modulations in kinematics (McNitt-Gray, 1993, Bobbert et al., 1986, Cappa and Behm, 2013). Indeed, it has been demonstrated that as drop height is increased an athlete may reach a point whereby the muscular response is reduced due to an inhibitory effect as demonstrated by a reduced H-reflex (Leukel et al., 2008b) and reduced power outputs (Lees and Fahmi, 1994). This may explain a failure to find augmented training adaptations past certain drop heights, as the optimal drop height will vary on an individual athlete basis (Bobbert, 1990).

A number of attempts have been made to define intensity during plyometric activity using measures of ground reaction force and neuromuscular activation (Ebben et al., 2008, Jensen and Ebben, 2007, Ebben et al., 2010b, Wallace et al., 2010, Ebben and Jensen, 2002, Sugisaki et al., 2013, Ebben et al., 2010a) - these are reviewed in more detail in section 2.3. Despite this attention within the literature, a consensus on the most suitable method of assessing

this form of exercise has remained elusive and research findings have, for the most part, failed to influence applied practice.

Ground reaction force data is the most frequently used methodology and may be processed to provide a number of metrics which may be insightful regarding the grading of exercise intensity. In addition to PF, Jensen & Ebben (2007) also compared rate of eccentric force development (E-RFD) as defined by the first peak of force divided by the time from onset of landing force to the first peak of force; finding significant differences between exercises which may suggest that the E-RFD may be a more sensitive measure than PF. Ebben et al. (2010a) used a wider range of force variables to measure intensity in plyometric exercises through landing PF, peak power and drive-off PF (also referred to as propulsion or concentric phase within the literature). This revealed differences in intensity ranking order depending on the force characteristic used. The dilemma of selecting the most suitable variable highlights an inherent problem in quantifying plyometric intensity as no accepted gold standard ranking method or order currently exists. More recently the assessment of force has been extended to examine the mechanical output at specific joints (Sugisaki et al., 2013). This approach found significant variation in the outputs at the hip and ankle joints between jumps. The contribution at the ankle joint was greatest for two-foot ankle hop and tuck jumps, while most hip joint variables were greatest for repeated squat jump or double-leg hop. These findings illustrate that the kinematic qualities of an exercise may have a marked influence on the training stimulus beyond consideration of global intensity. Consequently, exercises of similar intensity should not automatically be regarded as homogenous.

An alternative to the assessment of ground reaction forces is the use of sEMG to evaluate plyometric exercises. Ebben et al. (2008) and Simenz et al. (2006) produced contrasting findings to previous kinetic research and traditional opinion in terms of both the ranking order of intensity within the exercises used as well as the magnitude of difference. Exercises which are generally considered low intensity such as the counter-movement jump produced the highest levels of motor unit recruitment; in contrast high impact exercises such as a drop jump (from 30cm and 61cm) ranked lowest. The authors hypothesized that high stretching loads may enable greater utilization of the stretch-shortening cycle and thus more reliance on passive energy production. This may suggest that intensity is multi-

factorial with neuromuscular recruitment and mechanical demand both representing important factors which may be considered independent of one another. To date, no such system has been proposed which considers both these components of intensity.

The use of sEMG in plyometrics has been expanded by Cappa and Behm (2013) who compared forefoot and flat foot landings in hurdle and drop jumps. This study found that flat foot landings resulted in longer ground contact times (26%) with significantly higher rectus femoris sEMG activity (47%) in comparison with forefoot landings which induced a much greater rate of force development (45%). This supports the notion that the contribution of neuromuscular and elastic force production varies according to movement strategy. It also highlights an inherent weakness in the literature that small differences in kinematics (e.g. foot contact) may significantly affect the nature of an exercise and therefore broad definitions such as "drop jump" may not always be regarded as homogenous.

Exercise intensity may be considered from both internal and external perspectives. External intensity describes the load imposed upon the athlete and the outcome of the task, which can be described through the mechanical load and may be best quantified using ground reaction forces. Internal intensity describes the physical response required to overcome the external challenge, which can be measured through the neuromuscular response (via sEMG). The purpose of the present study was to evaluate the use of a range of force and sEMG variables for a variety of commonly prescribed jumping exercises (countermovement jump, a rebound jump, 30 cm drop jump, 40 cm drop jump, hop, rebound hop and 20 cm step-hop) and identify which of these differentiate between the intensity of the exercises. These may then be combined to produce a system of measurement which takes into account both the neuromuscular recruitment and mechanical loading of plyometric exercises and can be applied practically. It was hypothesized that, as with previous studies, the ranking order of exercise intensity will differ in terms of mechanical load vs. neuromuscular demand with ballistic exercises producing high muscle activation and plyometric exercises incurring a higher mechanical load.

3.4 Methods

3.4.1 Subjects

Seven adult male subjects (age 21.6 ± 0.9 years; mass 80.8 ± 7.2 kg) volunteered for the study. All subjects participated in recreational or intercollegiate sports and were familiar with the plyometric exercises evaluated in the study. Exercise technique was assessed and coached prior to and during the warm-up process to ensure a suitable standard of execution. Subjects were sports science students and were familiar with these common exercises. Subjects provided informed consent before participation in the study and ethical approval for the study was obtained through the Institutional Review board.

3.4.2 Exercise Protocols

Warm-up before the plyometric exercise consisted of 5 minutes stationary cycling at a self-selected pace. This was followed by 3 repetitions of each of the test exercises to provide opportunity for specific warm-up, coached practice and familiarisation.

Plyometric testing was preceded by a maximal voluntary isometric contraction (MVIC) in the leg extension and leg curl exercises to obtain reference data for sEMG normalization and comparison. MVIC testing was conducted using an isokinetic dynamometer (KinCom AP2, Chattanooga Group Inc., Chattanooga, TN, USA) which was locked to prevent movement at the knee joint. Subjects were secured at a fixed knee angle of 90° which was measured using a handheld goniometer. This joint angle was selected to replicate the protocols described by Schantz et al. (1989).

The exercises which were tested were a countermovement jump (CMJ), a rebound jump (RB), 30 cm drop jump (DJ30), 40 cm drop jump (DJ40), hop (Hop), rebound hop (RBHop) and 20 cm step-hop (Step) in a randomised order (Figure 3-1). The exercises used are popular training exercises which were all designed to be performed in the vertical plane to enable direct comparison. These were intended to provide a range of intensities as well as utilising differing challenges, namely: bilateral, unilateral, plyometric and ballistic jumps. These exercises are typical of those commonly used in athletic training and within the

plyometric literature (Ebben et al., 2008, Jensen and Ebben, 2007, Simenz et al., 2006, Wallace et al., 2010). Three consecutive repetitions of each exercise were performed with a minimum of two minutes rest between exercises in order to avoid accumulated fatigue. Subjects were supervised by a United Kingdom Strength and Conditioning Association (UKSCA) accredited strength and conditioning coach (ASCC). Coaching instructions were primarily directed towards ensuring safe and consistent technique with maximal effort. Subjects were guided to seek a minimal ground contact time whilst achieving maximal jump height. Cueing of exercises has been demonstrated to affect kinetic and muscle activation outcomes to a large extent (Cappa and Behm, 2013). Techniques which bias either the minimisation of contact time or achieving the greatest jump height have been categorised as the bounce and countermovement technique respectively (Marshall and Moran, 2013). The present protocol was designed to avoid a skewed bias towards either of these elements of jump characteristic to achieve a balanced performance profile. The ballistic jumps (CMJ and Hop) were performed with the arms held at the hips in order to minimise the technical demands of the exercises with a view to optimising consistent performance. Plyometric exercises (RB, DJ30, DJ40, RBHop and Step) were performed with the arms allowed to move freely. This technique was selected in order to allow subjects to remain balanced and perform the exercises most naturally.
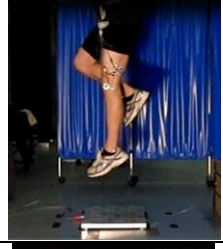
Exercise	Start	Mid	End
Countermovement Jump			
Rebound Jump			
30cm Drop Jump			
40cm Drop Jump			
Hop			
Rebound Hop			
Step Hop			

Figure 3-1 - Plyometric exercises

3.4.3 Electromyography

Surface EMG has been used in a number of studies as a means of estimating muscular activity during jumping activities (Aboodarda et al., 2014, Ball and Scurr, 2009, Peng et al., 2011, Toumi et al., 2001). Reliability and reproducibility of this technique during high speed, dynamic actions such as jumping and sprinting has been demonstrated as being high (Gollhofer et al., 1990, Goodwin et al., 1999, Fauth et al., 2010). Fauth et al. (2010) reported intrasession ICC values in excess of 0.8 when evaluating quadriceps and hamstring sEMG activity in two plyometric tasks; a drop jump landing and a cutting action following a 10m sprint. Gollhofer et al. (1990) evaluated the intersession reliability, which they describe as reproducibility, on sEMG assessment during running, hopping and drop jumping. The authors report "high qualitative reproducibility" as the shape of sEMG patterns remained consistent. Deliberate variability of electrode positioning resulted in significant changes in sEMG amplitude. These results suggest that evaluation of the muscle recruitment patterns may be robust against methodological error resulting from varied placement of electrodes, however, results are vulnerable to error when evaluating absolute activation levels. This may be a particular concern when seeking to compare multiple muscles and against a reference value such as MVC. The present study focussed on intra-session reliability and therefore inter-session reliability is not considered. However the importance of consistent electrode positioning between subjects is highlighted. Goodwin et al. (1999) compared the muscle specific inter-session reliability of sEMG assessment during countermovement jumping. A wide variation in reliability across muscle groups was found with rectus femoris demonstrating the highest reliability (ICC=0.88) whereas gastrocnemius reliability was the poorest (ICC=0.01). Vastus medialis and biceps femoris were also assessed with ICCs of 0.7 and 0.24 respectively. Little information is provided as to the training background of the 15 female subjects. The reliability of the measures may be affected by consistency of jumping technique. These findings would suggest that the prime mover contribution of the anterior thigh musculature to jump performance has the greatest degree of reliability in comparison with the posterior thigh and the plantar flexors.

The electrical muscle activity of the vastus lateralis (VL) and biceps femoris (BF) was recorded in the preferred jumping leg. These muscle groups were selected as being prime

movers of the lower-body during jumping (Pandy and Zajac, 1991) and replicated the methodology of McBride et al. (2008) and Peng et al. (2011). The rationale for selecting the preferred jump leg was based on the premise that subjects would be best familiarised with jumping from this leg and therefore these data were likely to be more consistently reproduced than the non-jumping leg. Bilateral sEMG assessment was rejected due to the technical complications presented by collecting this additional data (i.e. large numbers of electrodes required during highly dynamic movements).

Prior to placing electrodes, skin preparation involved shaving where necessary, exfoliation and cleansing with alcohol wipes. Electrodes were placed on the muscles in accordance with SENIAM guidelines for application, location, and orientation. VL electrodes were placed on the distal third of the muscle, BF electrodes were oriented along the line from the ischial tuberosity to lateral epicondyle. All loose wires were securely taped to minimise movement during jumping. Previous studies evaluating sEMG activity during plyometric activity have used frequencies of 1000-2000 Hz (Ebben et al., 2008, Sano et al., 2013, Cappa and Behm, 2013). A frequency of 2000 Hz was selected in order to achieve comparable data sets with the highest level of sensitivity within this range. Inputs were collected via figure of 8 shaped (40mm x 22mm) Ag/Ag Cl dual surface electrodes (Noraxon USA, Inc., Scottsdale, AZ) with an inter-electrode distance of 20 mm. The input impedance was >100 MOhms , signal to noise ratio of 0.2mV and the common mode rejection ratio was >100 dB. A superficial reference electrode was placed on the patella. Data were managed with MyoResearch XP Master (Edition v1.06.54). Saved sEMG data were full wave-rectified and integrated (sEMG in mV_s21). All data were filtered with a 10-Hz low-pass filter. A low-pass filter at this frequency has been consistently used within the literature with higher frequencies avoided to prevent the loss of sensitivity at low levels of activation (Fauth et al., 2010, Ebben et al., 2008). Processed sEMG data were analysed as concentric and eccentric phases. These distinct phases were identified using synchronised force data as described below.

3.4.4 Kinetic Assessment

The mechanical load of activities such as running and jumping have been measured via ground reaction forces extensively within the literature (McNitt-Gray, 1993, Jensen and

Ebben, 2007, Wallace et al., 2010, Ebben et al., 2011, Wang and Peng, 2014). Sampling frequencies as low as 200 Hz have demonstrated good reliability during jump exercises as found by Hori et al (2009). This study evaluated a range of kinetic variables from 25-500 Hz, using 500 Hz as a reference value. ICCs remained stable to 200 Hz (ICC=0.94) with reliability dropping below this frequency. This methodology did not extend to frequencies above 500 Hz which have been used regularly within the literature. Therefore it is not clear from these results whether a higher sampling frequency may yield greater reliability and sensitivity. Owen et al. (2014) sought to establish a criterion method of measuring power output during countermovement jumping. This study found differences in power outputs when comparing 1000 Hz, used as the criterion method, and both 100 Hz and 500 Hz. The authors did not investigate the possibility of a difference between results sampled at 1000 Hz and higher frequencies. Instead the assumption was made that the exponential decrease in variation seen across 100 Hz, 500 Hz and 1000 Hz would suggest a difference of <1% was likely. This presents a limitation as even differences below 1% may still be considered worth reducing. Furthermore this remains an assumption which is yet to be tested. The authors suggest that the convenience of sampling in time intervals of milliseconds and the likelihood of only minimal error make 1000 Hz a suitable frequency for accurate and practical force measurement.

Impulse has also been used widely across studies evaluating GRF in jump performances (Ebben and Jensen, 2002, McNitt-Gray, 1991, Ball et al., 2010, Coh and Mackala, 2013, Donoghue et al., 2011). Impulse offers an alternative perspective to other traditional variables which are based on peak values of a specific variable. Impulse provides a useful insight as, by describing the force exhibited across the entire movement and the duration of application, it provides perspective as to the nature of the force application rather than simply the peak value.

Given that plyometric exercise is typically associated with the rapid production of high forces it is logical that a measure of how quickly force is produced be incorporated into an assessment of intensity. This is not a new concept and is generally described as the rate of force development (RFD) (Aboodarda et al., 2014, Cappa and Behm, 2013, Cadore et al., 2013, Marques et al., 2015). This consideration as to the rate at which force is applied adds

another dimension to the kinetic picture which is not described by impulse. However, whilst conceptually valid, the use of RFD may be somewhat problematic due to the lack of an established and consistent methodology for determining RFD across the literature. This challenge is highlighted by Eagles et al. (2015) who performed a meta-analysis of the measurement of RFD. These results revealed a pattern of 3 common methods across the literature, each of which yielded different results on a common data set. Consequently it is desirable to identity a metric which considers a temporal aspect of force production in addition to the peak values attained.

A more novel variation of RFD has been used by Jensen & Ebben (2007) who investigated the use of eccentric RFD (E-RFD) to measure plyometric intensity. This study found greater sensitivity to detect differences in intensity in comparison with peak GRF. This variable is still subject to the potential inconsistencies identified previously. Furthermore, RFD (and E-RFD) may potentially mislead as exercises which involve low forces produced rapidly may be viewed as being of high intensity. An alternative solution is presented by the use of power as a measure of intensity as this represents a combination of force and velocity, which both underpin intense plyometric exercise (Ebben et al., 2011, Di Giminiani and Petricola, 2015, Gathercole et al., 2015a). Given that plyometric exercise is characterised by an overload of the SSC, the eccentric component of the movement is of particular interest. Therefore the present study used peak eccentric power (PEP) as a measure of intensity which considers both the speed of movement and the forces produced with the eccentric phase of movement.

A 60x40cm force platform (Model 9286AA Kistler, Winterthur, Switzerland), sampling at a frequency of 3,000 Hz, was used to measure ground reaction forces during all jumps. This sampling rate was selected in order to enable synchronisation with high speed video at 300 Hz should kinematic assessment be desired following analysis of results. Ground reaction force (GRF) data was recorded using Bioware V5.1.1.0 (Kistler) and processed using a custom Microsoft Excel 2010 spreadsheet. Processed GRF data was used to derive a number of variables intended to provide a greater level of insight into the mechanical stresses involved, namely: PF, impulse and peak eccentric power. The method of calculation for these is described in Table 3-1.

Table 3-1 - Calculation of force variables

Force Variable	Method of calculation
Peak Force (PF)	Taken as the highest ground reaction force value across the impact and concentric phases of a jump.
Displacement	Calculated from double integration of the acceleration graph. Change in height from onset of movement to minimum value is calculated.
Impulse (IMP)	The area under the force-time curve. Taken using the absolute* vertical GRF. The trapezium rule was used to calculate the area by through the following formula: *Time interval between measurements = 1/sample frequency* *Area between 2 consecutive force reading F1 and F2 = (F1 x t)+ 0.5((F2 - F1) x t)*
Peak Eccentric Power (PEP)	Velocity was determined by integrating acceleration data, power was then determined by multiplying the corresponding absolute force and velocity values. Maximum eccentric power was taken as the minimum value during the eccentric phase.

*Absolute GRF was used as comparisons were made between exercises by each subject rather than between subjects. Between subject comparisons would require the use of relative GRF in order to remove avoid error resulting from differing body weights.

PF has been used consistently within the literature when assessing plyometric intensity (McNitt-Gray, 1993, Ebben et al., 1999, Ebben et al., 2010a, Ebben et al., 2011, Jensen and Ebben, 2007, Wallace et al., 2010, Ball et al., 2010, Donoghue et al., 2011, Wong et al., 2012). As a representation of the highest level of mechanical stress experienced during an exercise, PF is a logical choice of metric to assess intensity. PF also has the advantage of requiring little processing which makes comparisons across studies more robust and in an applied setting makes coach-athlete feedback relatively simple. Differences in smoothing techniques and sampling frequencies are likely to be the primary sources of error when comparing data. PF may enable further analysis of performance when distinct phases of the GRF are considered, namely; rebound impact, eccentric phase, and the concentric phase. These are illustrated in Figure 3-2.
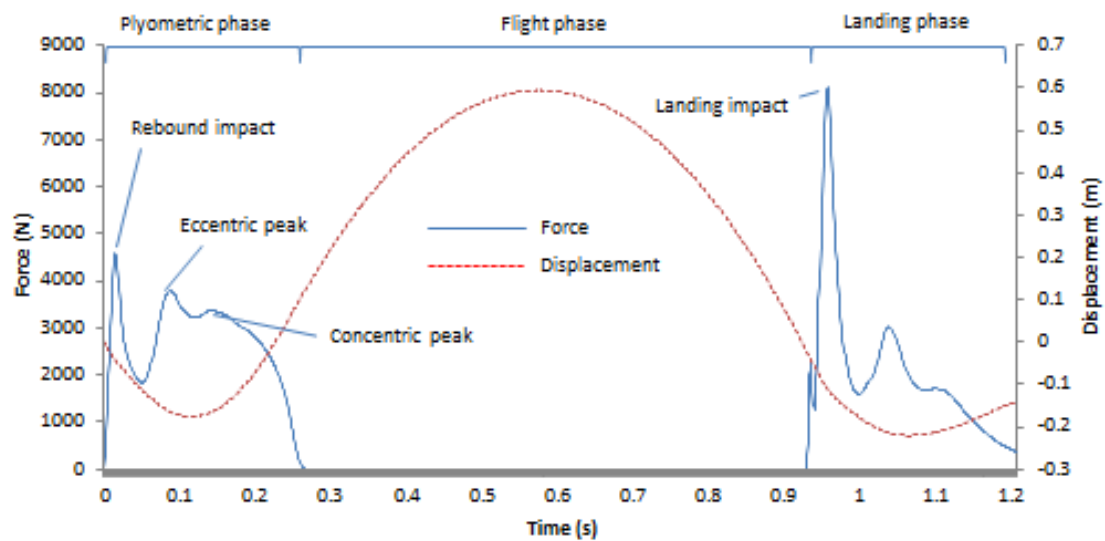
Figure 3-2 - Example force trace from a drop jump to illustrate phases

Whilst there may be merit in identifying the PF associated with each of these distinct elements of a movement to better understand the nature of the forces which an individual produces and is subjected to, the present study in concerned with the peak value across the movement as a whole. This is based on the rationale that understanding intensity should primarily be determined by identifying the highest level of stress that an individual must tolerate.

Force and sEMG data collection were synchronised using an interface box (Kistler, 5606A) and utilised a sampling period of 6 seconds to allow subjects to perform the task without haste. Concentric (CON) and eccentric (ECC) phases of each jump were identified using force data. During plyometric jumps the eccentric phase of movement was deemed to commence at the start of ground contact defined as the first rise in force above 20 N. This is an arbitrary figure which was intended to provide a threshold above noise within the signal and subsequent "false landings". In ballistic jumps the start of the eccentric phase was deemed to commence at the initiation of movement defined as the first drop in force of 20 N below body weight (BW). The end of the eccentric phase was taken as the time point of minimum depth based on displacement calculations. Concentric phase start point for all jumps was taken as beginning immediately following the eccentric phase. The concentric phase finished at the end of ground contact as represented by zero force. The time points

identified as representing each of these phases was used to assess and describe the eccentric and concentric movement components in both force and sEMG.

3.4.5 Data Analysis & Statistics

The statistical analyses were undertaken with SPSS V17.0 for Windows (SPSS, Inc., Chicago, IL) using a one-way repeated-measures analysis of variance using a Tukey post-hoc analysis to test for main effects for kinetic data as well as the mean concentric and eccentric sEMG activity in both the BF and VL within each exercise. The level of significance was set at $p \leq 0.05$ for all analyses. All jump data satisfied parametric assumptions as determined through the Shapiro-Wilk test. Intraclass correlation coefficients (ICCs) were calculated using a two-way random effects model to determine relative reliability within trials which were interpreted as high reliability if $r \geq 0.80$ (Cortina, 1993). Descriptive statistics (mean ± SEM and SDD) were computed for the variables above. Smallest detectable difference (SDD) was calculated using the following formula: $(1.96 \times \sqrt{2} \times SEM)$ (Cormack et al., 2008). Partial Eta square effect size (ES) statistics were conducted to evaluate the magnitude of the difference in exercises. Statistical power was calculated using G*Power v3.1 (Faul et al., 2009).

3.5 Results

The effect sizes of all sEMG and kinetic variables are described in Table 3-2. The mean, SEM, ICC and SDD data illustrating the reliability of sEMG and force data are described in Table 3-3, Table 3-4, and Table 3-5. Effect sizes were large for kinetic variables (0.7-0.9) and small to moderate for sEMG variables (0.06-0.41).

Table 3-2 - Effect sizes of kinetic and sEMG variables across exercises

Variable	Con BF	Con VL	Ecc BF	Ecc VL	Relative IMP	Relative PEP	Relative PF
η^2	0.06	0.11	0.18	0.41	0.9	0.8	0.7

Ecc BF = eccentric biceps femoris; Con BF = concentric biceps femoris; SEM = standard error of the mean; ICC = intraclass correlation coefficient; SDD = smallest detectable difference

Table 3-3 - Mean, SEM, ICC and SDD values for the sEMG in VL

Exercise	Ecc VL				Con VL			
	Mean (%MVIC)	SEM	ICC	SDD	Mean (%MVIC)	SEM	ICC	SDD
CMJ	68	5.7	0.97	15.9	149	17.1	0.99	47.5
RB	133	13	0.82	36	117	12.6	0.96	34.9
DJ30	153	15.8	0.89	43.9	141	8.6	0.86	23.8
DJ40	141	14.5	0.738†	40.3	137	9.6	0.86	26.6
Hop	134	5	0.83	14	114	9.4	0.92	26.2
RB Hop	61	11	0.89	30.6	153	8.8	0.92	24.3
Step	137	11.3	0.95	31.3	139	12.6	0.9	35.1

Ecc VL = eccentric vastus lateralis; Con VL = concentric vastus lateralis; SEM = standard error of the mean; ICC = intraclass correlation coefficient; SDD = smallest detectable difference
†Alpha below threshold value of 0.8

Table 3-4 - Mean, SEM, ICC and SDD values for the sEMG in BF

Exercise	Ecc BF				Con BF			
	Mean (%MVIC)	SEM	ICC	SDD	Mean (%MVIC)	SEM	ICC	SDD
CMJ	23	1.4	0.98	3.8	68	4.7	0.86	13.0
RB	46	4.6	0.95	12.8	133	4.5	0.96	12.4
DJ30	50	5.0	0.96	13.8	153	5.6	0.94	15.6
DJ40	47	4.8	0.97	13.3	141	5.7	0.92	15.8
Hop	52	1.7	0.92	4.8	134	4.1	0.95	11.3
RB Hop	22	5.5	0.99	15.2	61	7.2	0.94	20.0
Step	48	5.0	0.96	13.7	137	3.8	0.92	10.5

Ecc BF = eccentric biceps femoris; Con BF = concentric biceps femoris; SEM = standard error of the mean; ICC = intraclass correlation coefficient; SDD = smallest detectable difference

Table 3-5 - Mean, SEM, ICC and SDD values for Force Variables

Exercise	Rel PF				Rel PEP				Rel IMP			
	Mean N/BW	SEM	ICC	SDD	Mean (W/BW)	SEM	ICC	SDD	Mean Ns/BW	SEM	ICC	SDD
CMJ	2.5	0.1	0.96	0.2	-1.66	0.1	0.95	0.3	2.46	0.26	0.91	0.10
RB	4.48	0.4	0.90	1.0	-7.53	0.7	0.92	2.0	5.03	0.30	0.96	0.29
DJ30	3.79	0.2	0.85	0.6	-7.61	0.4	0.91	1.2	4.48	0.31	0.99	0.10
DJ40	4.4	0.3	0.97	0.9	-10.26	0.6	0.97	1.7	4.68	0.30	0.97	0.10
Hop	1.86	0.0	0.99	0.1	-0.99	0.1	0.88	0.3	1.54	0.43	0.94	0.10
RB Hop	2.92	0.1	0.87	0.3	-4.04	0.3	0.93	0.7	3.35	0.57	0.96	0.29
Step	2.52	0.1	0.87	0.3	-4.61	0.3	0.85	0.7	3.29	0.24	0.93	0.10

Rel PF = relative peak force; Rel PEP = relative peak eccentric power; Rel IMP = relative impulse; SEM = standard error of the mean; ICC = intraclass correlation coefficient; SDD = smallest detectable difference

Means of sEMG during eccentric and concentric phase activity in VL and BF demonstrate high reliability r ≥0.82, excluding Ecc VL during DJ40 which only demonstrated moderate reliability (r=0.74). Peak ground reaction force (PF), peak eccentric power (PEP) and impulse (IMP) represent force derivatives which have both a theoretical relevance to plyometric intensity and also demonstrate high reliability (r≥0.85).

Statistical power for force variables was excellent (Power = 1.0), and good for sEMG (Power ≥0.86) excluding CON BF (Power = 0.57).

Eccentric sEMG activity in VL during CMJ and Hop was lower than all other jumps (p<0.05) although there was no significant difference between CMJ and Hop (see Figure 3-3). The same pattern was also seen in eccentric BF activity (see Figure 3-4). No significant differences were seen between jumps in sEMG activity during the concentric phase in either VL or BF (see Figure 3-5). However sEMG in VL and BF showed high variability and very high SDD. This is likely due to differences in landing strategies.
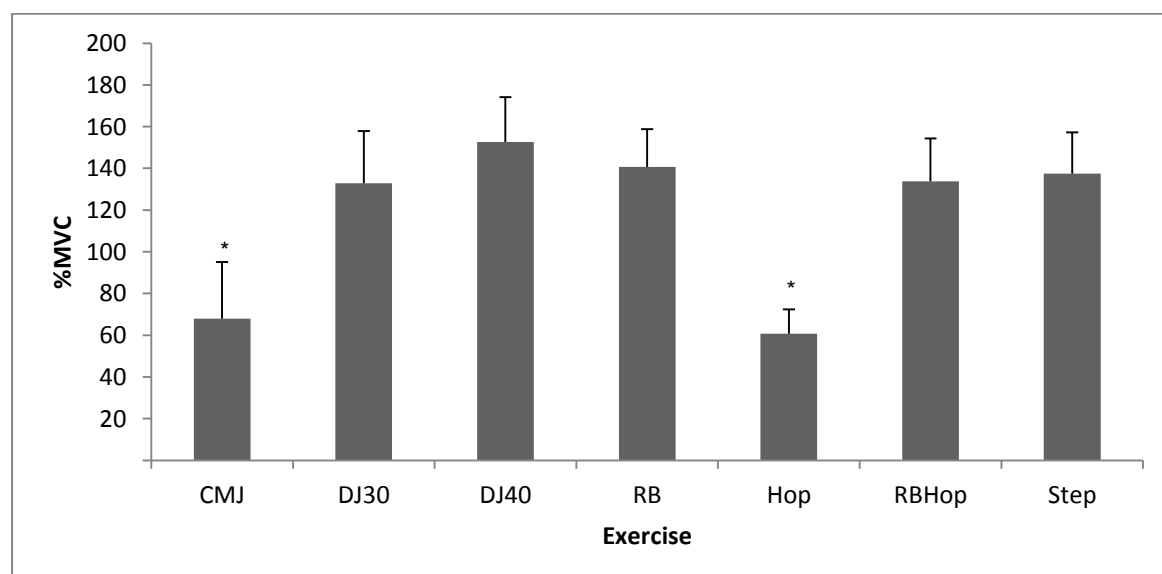
Figure 3-3 A comparison of mean Ecc sEMG in VL across exercises
* Significantly different (p<0.05) than RB, DJ30, DJ40, RBHop and Step
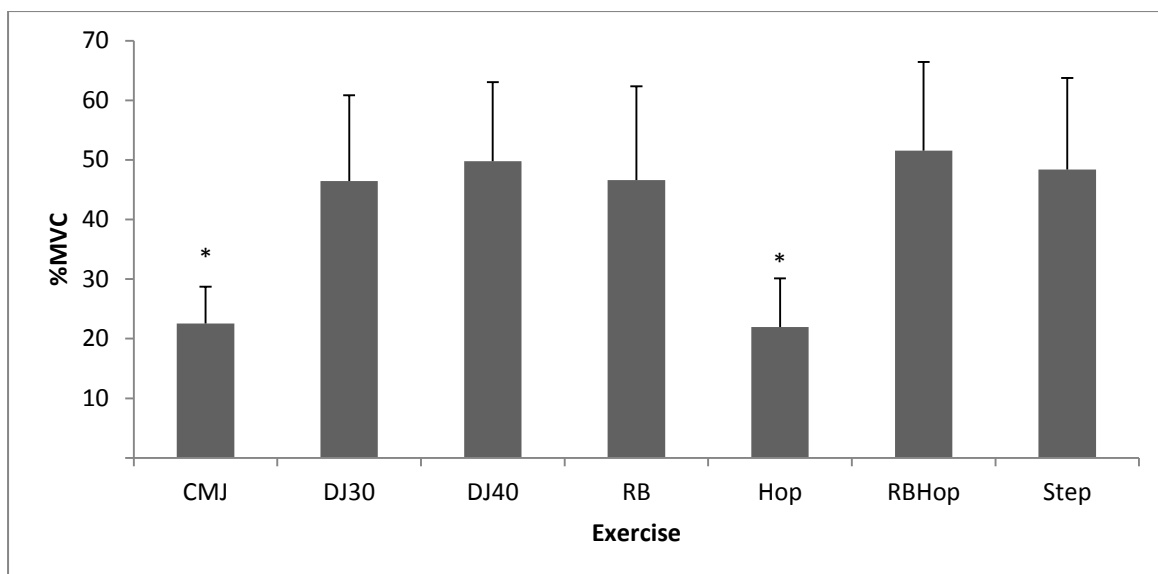
Figure 3-4 - A comparison of mean Ecc sEMG in BF across exercises
* Significantly different (p<0.05) than RB, DJ30, DJ40, RBHop and Step
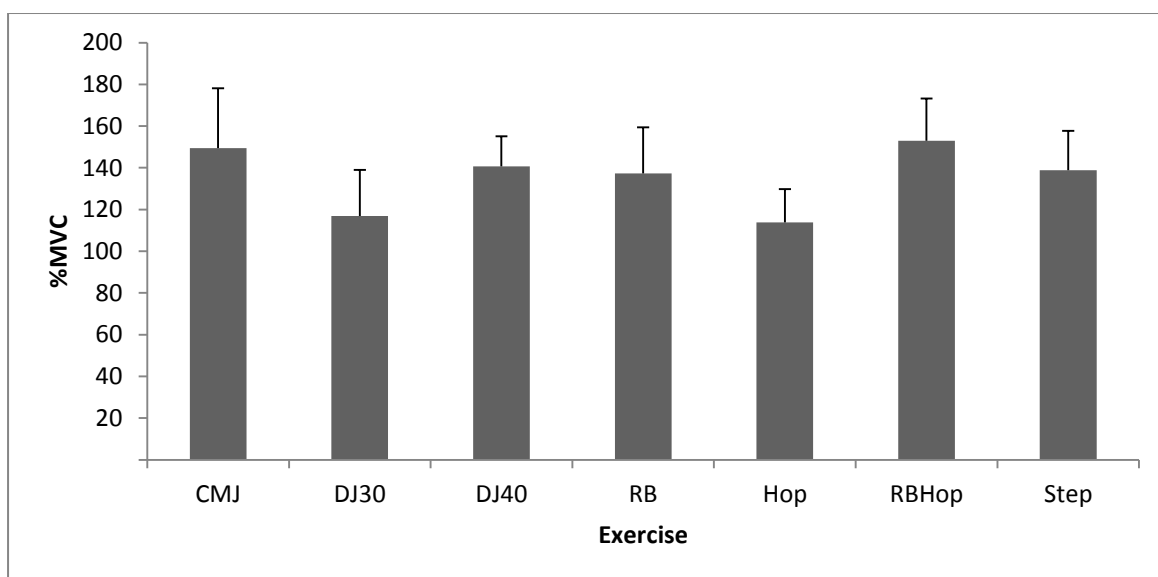
Figure 3-5 - A comparison of mean con sEMG in VL across exercises

Force variable data (GRF, Impulse and Ecc Power) are illustrated in Figure 3-6, Figure 3-7 and Figure 3-8.
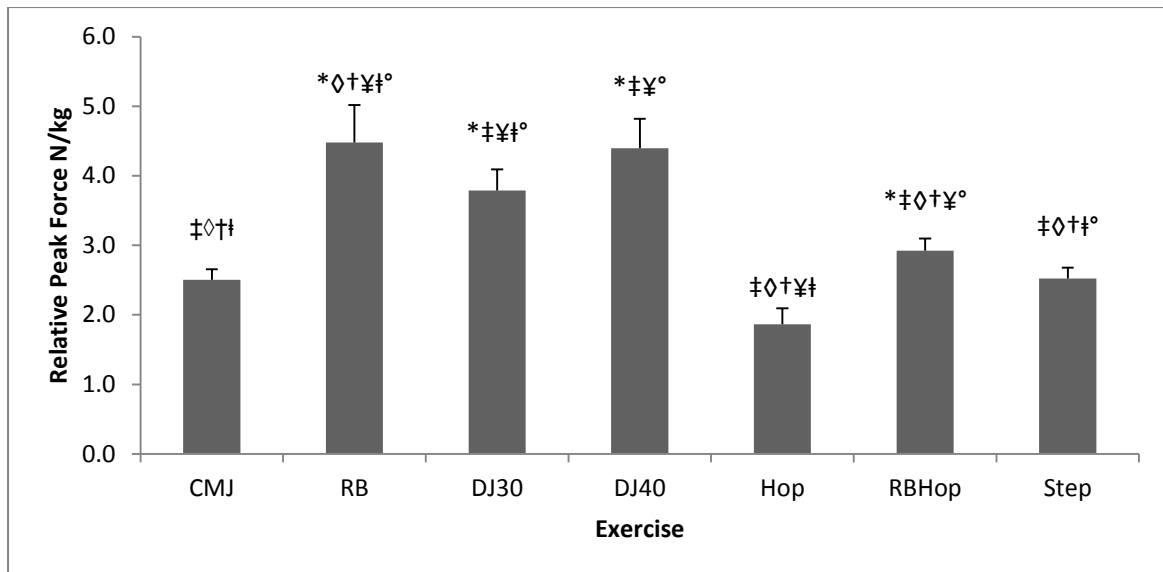
Figure 3-6 - A comparison of means of relative PF across exercises

* Significantly different (p<0.05) than CMJ

† Significantly different (p<0.05) than RB

‡ Significantly different (p<0.05) than DJ30

◊ Significantly different (p<0.05) than DJ40

ⱦ Significantly different (p<0.05) than Hop

¥ Significantly different (p<0.05) than RBHop

° Significantly different (p<0.05) than Step
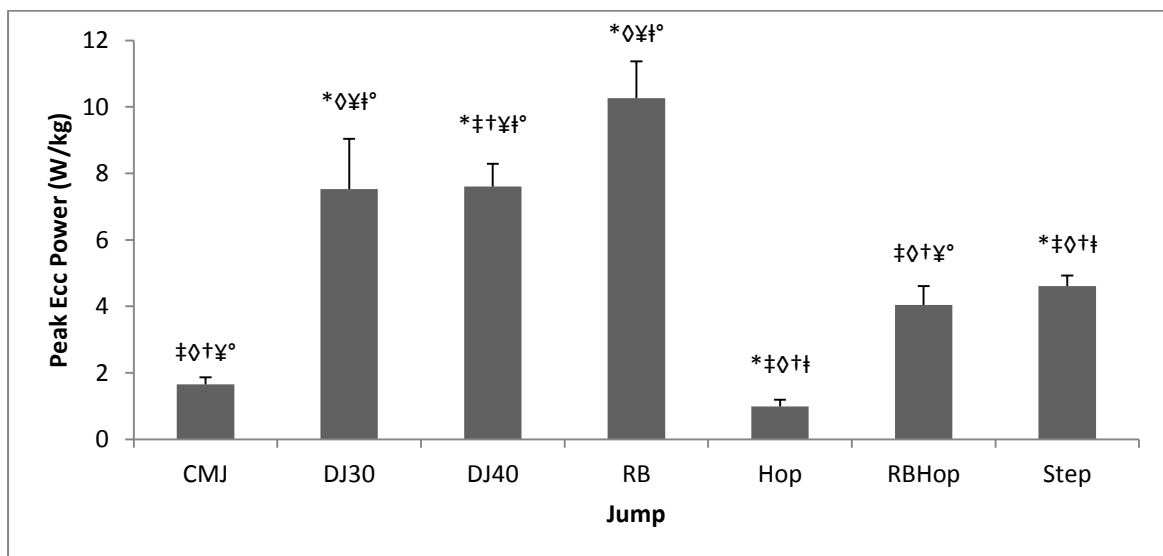
Figure 3-7 - A comparison of means of relative peak eccentric power across exercises

* Significantly different (p<0.05) than CMJ

† Significantly different (p<0.05) than RB

‡ Significantly different (p<0.05) than DJ30

◊ Significantly different (p<0.05) than DJ40

ⱦ Significantly different (p<0.05) than Hop

¥ Significantly different (p<0.05) than RBHop

° Significantly different (p<0.05) than Step
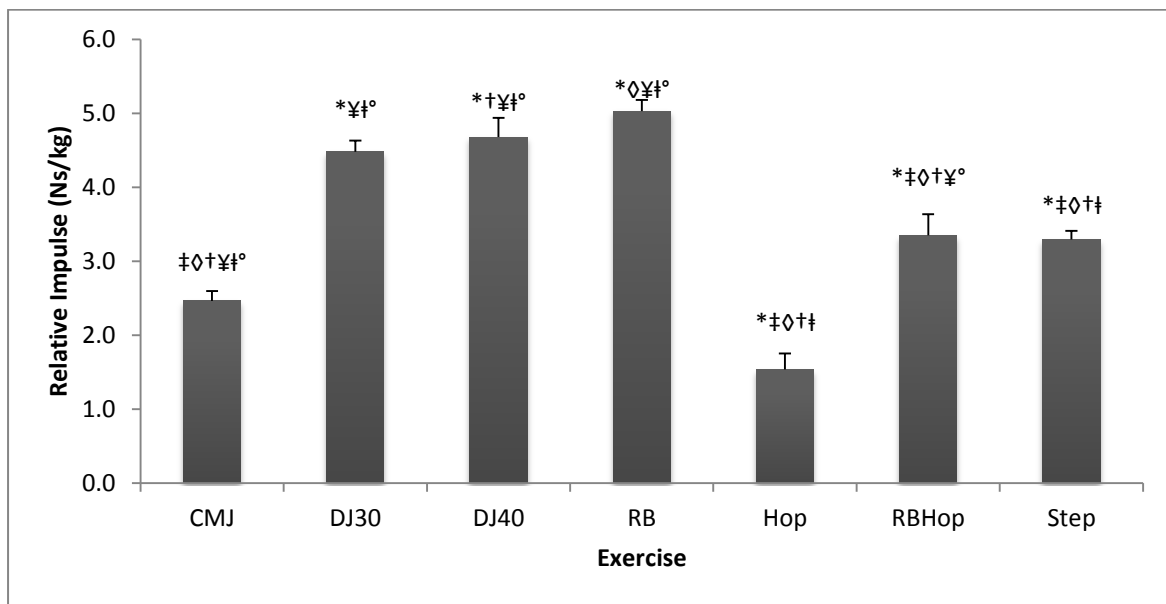
Figure 3-8 - A comparison of means of relative impulse across exercises

* Significantly different (p<0.05) than CMJ
† Significantly different (p<0.05) than RB
‡ Significantly different (p<0.05) than DJ30
◊ Significantly different (p<0.05) than DJ40
ǂ Significantly different (p<0.05) than Hop
¥ Significantly different (p<0.05) than RBHop
° Significantly different (p<0.05) than Step

3.6 Discussion

The results from the present study partly confirm the hypotheses that differences exist between the neuromuscular and mechanical intensity of plyometric exercise. However, contrary to previous studies, neuromuscular activation and force characteristics both suggest a greater level of intensity in plyometric activities over ballistic variations. Whilst neuromuscular intensity appears homogenous within the categories of ballistic and plyometric activities, force variables may be used to rank intensity of exercises with greater distinction.

3.6.1 Muscle Activity

sEMG activity may be considered an indicator of the neuromuscular demands of an exercise and has previously demonstrated good reliability (Gollhofer et al., 1990, Fauth et al., 2010), with statistical analysis of the present results revealing that mean sEMG of Ecc VL, Con VL, Ecc BF and Con BF all demonstrate good relative reliability (ICC r≥0.74). However the capacity of sEMG variables to differentiate between exercises of varying intensity was poor with effect sizes considered low with the exception of Ecc VL.

No significant difference in muscle activity was found between exercises during the concentric phase for VL or BF. All exercises were performed with maximal intent and therefore it appears that, providing this condition is met, neural drive and muscular activation during the concentric phase of plyometric activity may not differ between exercises. These findings are in agreement with previous studies which have shown that in pre-stretch vs pre-isometric conditions there is no difference in concentric sEMG activity despite enhanced force production (Thomson and Chapman, 1988, Walshe et al., 1998, Finni et al., 2001).

Eccentric activity in VL and BF was significantly lower ($p<0.05$) in CMJ and Hop in comparison with all other jumps. The magnitude of this difference was approximately double compared to each of the other plyometric exercises. No significant difference was observed between the other jumps or between CMJ and Hop. CMJ and Hop do not require the athlete to absorb a landing impact; therefore a distinction can be made between plyometric and ballistic activities. These findings support the classic model proposed by Siff and Verkoshansky (2009) which broadly categorises jumping exercises as plyometric or ballistic.

The present findings demonstrate a homogenous sEMG response within ballistic and plyometric categories which is in contrast to previous sEMG evaluations of plyometric exercises which have shown significant variation (Simenz et al., 2006, Ebben et al., 2008, Cappa and Behm, 2013). Conclusions regarding this disagreement are hard to draw given the nature of plyometric exercise descriptions. The movement descriptors give only an approximate guide to the mechanics involved. However significant mechanical differences

including range of movement, foot contact and joint angle distribution may exist within an exercise. These could potentially result in changes in neuromuscular activity. Cappa and Behm (2013) demonstrated significant changes in neuromuscular activity with changes in foot contact type. The sEMG data in VL and BF in the present study showed high variability and very high SDD. Consequently the data may have lacked the sensitivity to detect small differences between exercises within the ballistic and plyometric subcategories. The high variability may be due to variation in landing strategy. Bobbert (1990) describes 2 distinct strategies during the drop jump exercise; the bounce drop jump and the countermovement drop jump. The former is characterised by an attempt to rapidly rebound off the ground whereas the latter utilises a longer absorption time. Cappa & Behm (2013) demonstrated that these differing techniques have significant effects on muscular activation patterns. They also found foot placement to influence muscular activity, particularly in the calf musculature but this was not assessed in the present study.

The regular monitoring of sEMG data during training is not a practical solution to most coaches given the time required for preparation, expense of equipment and time and expertise required to assess the data. Furthermore the methodology may lack the sensitivity required to make precise programming decisions due to the small effect sizes. The present findings suggest that regular monitoring may not be necessary when considering the intensity of muscular activity during plyometric exercise. If concentric work is of interest then the absence of detectable difference in concentric muscle activity between exercises within the present study suggests that this will be matched between exercises providing the athlete's exertion is maximal. Therefore the coach may be best advised to select movements which are similar in joint angle (hips, knees and ankles) and ground contact time to the action they wish to enhance.

High levels of eccentric activity are a key feature of plyometric exercises, as demonstrated by the two-fold increase in eccentric muscular activity between plyometric and ballistic exercises. Therefore eccentric muscular activity represents an important component of intensity. It appears that the height from which the athlete falls has little bearing on the level of eccentric muscular activity of the VL or BF. By categorising exercises as plyometric or ballistic it is possible to make inferences as to the degree of eccentric muscular activity which will be achieved. Much variation and debate has existed amongst coaches as to the

falling height used during drop jumping. Bobbert (1990) found no difference in performance gains in terms of jump height between jumps from different heights. This supports the present findings that muscular activity is matched across plyometric challenges, regardless of the exercise variation. It has also been suggested that neural drive is reduced when the landing challenge is too great, such as jumping from a very high box (Leukel et al., 2008b). However it should be noted that this effect was not evident within the present results, although this may be explained by the relatively modest drop heights used in comparison with the previous study. Coaches may be best advised to take a conservative approach to box height selection, unless focussing on eccentric training and landing mechanics for injury prevention purposes.

Within the literature it has been reported that the mechanical output per leg is lower in bilateral jumps than unilateral (Challis, 1998, Vint and Hinrichs, 1996). This phenomenon is known as the bilateral deficit and has been attributed to a reduced neural drive. However, no difference in neural drive was evident between unilateral and bilateral exercises in the present study. These results are supported by the findings of (Bobbert et al., 2006) who suggest that the reduced mechanical output is the result of faster shortening velocities rather than reduced activation. Consequently the internal intensity of plyometric exercise does not differ between unilateral and bilateral challenges.

3.6.2 Ground Reaction Forces

Plyometric intensity has been defined as, "the amount of stress placed on involved muscles, connective tissues, and joints and is dictated by the type of plyometric exercise that is performed" (Potach and Chu, 2000), p.433. Whilst ground reaction forces do not directly describe the specific stresses placed on these individual structures, the mechanical load and subsequent stress placed upon the body is a key consideration in training intensity (Crewther et al., 2005, Benjamin and Hillen, 2003). This has been shown to be important in the regulation of IGF-I and specifically mechano-growth factor (Bamman et al., 2007, Heinemeier et al., 2007). These represent primary stimuli for myofiber hypertrophy and collagen synthesis within tendons which are directly related to the degree of mechanical stress experienced, although the interaction effects between intensity and volume are

unclear. Consequently some measure of force must be considered in the quantification of plyometric intensity.

The load during plyometric exercise is a product of the athlete's mass, falling height, ability to resist yielding (flexion of the ankle, knee and hip) and applied force. These in turn are a product of the athlete's physical abilities, exercise characteristics, self-selected landing strategy and coaching cues. The complex interaction of these factors dictates that direct measurement of ground reaction forces is required to quantify the mechanical loading of a plyometric exercise. Force data can be manipulated to produce derivative variables which reflect different aspects of performance. When considering the most appropriate variable three factors must be considered: reliability, validity and sensitivity. PF, peak eccentric power (PEP), and impulse (IMP) all demonstrated good relative reliability across the series of jumps exercises with impulse showing the greatest levels of reliability (mean ICC = 0.92, 0.91, 0.95). Sensitivity of PF and PEP was moderate (mean SDD = 15.1%, 18.8%) with greatest sensitivity shown in IMP (mean SDD = 4.3%). The effect sizes of exercises on these 3 variables were similar (0.7-0.9) with IMP demonstrating the largest effect size.

Siff & Verkoshansky (2009) suggest impulse as a valid measure of plyometric intensity (p.272). IMP is an appealing metric as the total mechanical load during a movement is accounted for and therefore the jump as a whole rather than the peak is considered. The ground contact time and pattern of force application may differ considerably between exercises. In such a scenario impulse enables direct comparison of exercises which differ in terms of force distribution patterns (Tsarouchas et al., 1995). However, some level of detail may be lost if IMP alone is used to measure intensity as the peak level of mechanical stress experienced by the athlete may be masked. Therefore impulse may be best considered alongside PF. It is important to be able to distinguish between high force, brief contact exercises and lower force movements with longer contact times. The sensitivity of IMP during the present study was very high and distinctions were made between all exercise with the exception of the 30 cm drop jump and 40 cm drop jump although there was a non-significant trend (p=0.28). This is in agreement with previous research which has found IMP to differ across plyometric exercises (McNitt-Gray, 1991, Ebben and Jensen, 2002)

Unlike IMP, both PF and PEP represent variables which describe the highest level of mechanical stress experienced during a plyometric exercise. Both demonstrate good reliability and sensitivity. Therefore by using either of these in conjunction with impulse it is possible to quantify both the absolute intensity of an exercise as well as the accumulated work. Such a system represents an accurate reflection of the mechanical demands of a plyometric challenge.

PF has been used previously to describe intensity (Tsarouchas et al., 1995, Jensen and Ebben, 2007, Wallace et al., 2010). Relative PF (Rel PF) expressed in BW (N/kg) is easily conceived by coaches and athletes and allows simple comparisons between individuals and activities. Similar to these previous studies the present results show increasing PF with greater drop heights. It is of note that the Rel PF are higher in this study than those within the literature. For example, a 40 cm drop jump produced a Rel PF of 4.4 N/kg compared with 2.9 N/kg (Wallace et al., 2010) and 3.3 N/kg (Jensen & Ebben, 2007). This is despite the participants in the previous studies being described as elite. A high Rel PF may be indicative of high functional strength as it reflects the ability of the athlete to resist yielding. Previous pilot data we have collected with elite jumpers found relative peak GRF of 8.3 N/kg in a 40 cm drop jump.

PEP gives consideration to both the absorption of impact forces and the rate at which the work is performed. PEP also demonstrated high levels of sensitivity as distinctions were made across the jump series. This is similar to the findings of (Jensen and Ebben, 2007) who found eccentric rate of force development to differentiate between exercises with a greater level of sensitivity than PF.

The use of force data to compare bilateral exercises with unilateral tasks provides a complex challenge. Assuming an even left-right distribution of force during bilateral tasks, a unilateral exercise involving the same level of force will subject a 2-fold increase in forces through the lower limb. However this may be a somewhat simplistic view as the pelvis and trunk are also important areas in the successful performance of jumping exercises. During unilateral tasks this musculature is generally required to work isometrically against rotation to a much greater extent than during bilateral movements. This may be more appropriately described as different rather than more intense. If the focus of the exercise is purely the

strength of the lower limb then doubling PF and IMP to compare with bilateral exercises may be appropriate although it should be recognised that this may be a somewhat over-simplistic view of the global stress placed on the individual beyond that which the lower limbs are subject to.

One novel approach to the comparison of unilateral and bilateral loadings is to consider body segment contributions (Graham-Smith et al., 2015). Such an approach is based on the segmental weight distributions acting above or rotating about the hip joint(s) in single-leg and double-leg squat or jump movements. The combined segmental BW acting above the hips in a double-legged movement has been estimated at 68% and at 84% in a single-legged movement (de Leva, 1996). Thus it is possible to estimate single-leg forces on the basis of the following equation:

$$Single\ leg\ force = 0.81\ x\ double\ leg\ force\ (where\ 68/84 = 0.81)$$

At present this approach remains speculative and further research is required to evaluate the efficacy of the theoretical approach and the specific equation proposed.

The present findings provide a number of variables which may be used to describe the global intensity of plyometric exercises. The power of this system may be enhanced by evaluating specific joint mechanical outputs in order to gain greater precision in exercise prescription as suggested by Sugisaki (2013).

3.6.3   Limitations

Perhaps the biggest limitation to this study is the small sample size. This is primarily a reflection of the challenge of capturing multiple sources of data during the performance of highly dynamic exercise. The study was hampered on several occasions by technical failure which resulted in a smaller sample size. However despite this, high statistical power was observed across all variables with the exception of concentric sEMG.

The sample population within the study can be considered highly homogenous (i.e. young recreationally active males). Replication of these findings in other populations would add to the power of the present findings.

The assessment of reliability in this study is restricted to within session reliability rather than between session reliability. The rationale for this is the intention to demonstrate the capacity of variables to distinguish between exercises rather than of the athlete to reproduce consistent measures. Future studies applying this assessment system to monitor an athlete or group of athletes will require an understanding of between session reliability in order to evaluate meaningful differences.

A number of jumping studies have evaluated the muscular activity of gastrocnemius during jump studies (Ebben et al., 2008, Cappa and Behm, 2013). This is a logical inclusion given the role of the ankle in jumping tasks. The inclusion of gastrocnemius is common but cannot be considered mandatory as a number of studies have used the approach taken within this study of focussing on the activity of the anterior and posterior thigh during jumping (McBride et al., 2008, Peng et al., 2011). The decision not to monitor gastrocnemius activity in this study was due to the added complexity and increased risk of technical failure with the inclusion of additional muscles. Future studies may add to the present findings by including gastrocnemius and other muscles such as soleus and gluteus maximus which also play a role in jumping.

Surface EMG assessment in this study used the dominant leg only rather than making a bilateral assessment. Clearly there is the potential that this additional level of information may have provided additional insight. In this instance it was concluded that unilateral monitoring would provide sufficient insight and that the added complexity of attempting bilateral measurement was not off-set by the potential for greater richness of data. This was particularly important given the technical challenges referred to previously. A number of studies within the literature have made a distinction between plyometric activities with different coaching cues. This includes the categorisation of drop jumps as "bounce" or "counter-movement" jumps (Marshall and Moran, 2013). These terms refer to the athlete placing an emphasis on a brief ground contact time (bounce) or large forces and maximal height (countermovement). These binary categories do not reflect that these are scale metrics rather than nominal. However this approach does highlight the potential for variability of execution within a given task. Subjects in the present study were instructed to achieve the maximum height with the minimum contact time, thus achieving a balance between the two extremes. In order to achieve the highest level of validity these factors

need to be controlled through appropriate cueing, familiarity, and monitoring as much as possible. However it must be acknowledged that individual technique is likely to result in some degree in variation in this regard. The restriction of the use of the arms in ballistic jumps which was not enforced during plyometric exercises should be acknowledged as a limitation.

It is noted that the use of an arbitrary threshold of a drop of 20 N below BW to denote onset of movement in ballistic jumps may be inferior to the method described by Owen et al. (2014) which recommends that a value of 5xSD of BW be used. This study was conducted prior to the publication of these recommendations and it is not felt that the robustness of the data has been compromised. However it may be preferable to adopt recommended guidelines in future studies.

When wishing to make an assessment of an athlete during jump performance, a more elaborate and specific warm-up than that used within this study may be desirable. The present warm-up may be considered somewhat limited due to the absence of progressive dynamic movements and the limited number of practice repetitions.

Finally, further research is required to explore the distribution of PF across the specific phases of a jump. This will provide greater understanding as to the nature of the forces which an athlete is subject to as well as providing a greater understanding of the demands of a specific exercise.

3.7 Summary

The present results provide a robust evidence base for the use of kinetic variables as the most appropriate means of describing volume and intensity of plyometric and ballistic exercise. Such a system provides researchers and practitioners with a methodology to gain greater insight into the demands of these important forms of training.

Measures of muscular activation clearly illustrate an enhanced neuromuscular contribution during plyometric versus ballistic activities. It is also clear that neural drive remains unaffected by unilateral vs. bilateral challenges. These results lend support to the theory that the increased mechanical outputs exhibited during increasingly high impact plyometrics

are largely the result of elastic energy production rather than increased neuromuscular activity.

Coaches may achieve greater precision of plyometric prescription through the use of PF to describe exercise intensity in favour of traditional measures such as drop height. The former is advantageous as it describes the outcome of the performance rather than the potential of the exercise. The use of IMP to measure the session volume may also give coaches greater sensitivity when comparing similar exercises than the traditional approach of counting foot contacts. The utility of such a practice will depend to a large extent on the opportunity to test athletes directly or to be able to make reasonable estimates of PF based on similar populations along with the assumption of technical consistency in jump performance.

Strength and conditioning coaches are also encouraged to place significant attention on the kinematics of exercise selection and coaching cues as deviations within an exercise challenge may result in substantial changes in neuromuscular activation patterns and mechanical output at different joints (Cappa and Behm, 2013, Sugisaki et al., 2013).

The next study within this thesis will apply these kinetic methods of assessment to an elite athletic population to extend understanding of the nature of training stress within this group of elite performers for whom jump exercises are a key training methodology.

Chapter 4 – Comparisons of Intensity & Volume Across a Range of Jump Exercises in Elite Male Track & Field Athletes.

4.1 Overview

In the previous study, a methodology for the evaluation of intensity and volume within plyometric and ballistic exercise was established using kinetic variables. The present study will apply this methodology to evaluate the demands of plyometric exercise in elite male track and field athletes. This study will build upon the findings of the previous study and will utilise a more discrete analysis of ground reaction PF by analysis of movement in specific phases of the exercises. Gaining a greater understanding of the demands of jump exercises within this group has the potential to provide insight to practitioners working with elite populations although the utility may not be exclusive to this group.

4.2 Abstract

The purpose of this study was to evaluate the demands of popular plyometric exercises within an elite male track and field population. Ten elite athletes performed four different jumping exercises with ground reaction force data collected via a force platform. PF was used as a measure of exercise intensity with impulse representing volume-load. The methodology of the previous study was expanded to include an assessment of intensity by movement phase; impact, braking, concentric and landing phases, as appropriate. Ground reaction forces showed high reliability (ICC=0.81-0.99) and the exercises used elicited a broad range of intensities ranging from 2.97-7.24 N.kg with large and significant differences observed across exercises. Ballistic exercises produced the lowest PF despite longer movement times (CMJ = 2.97 ± 0.12 N.Kg, 0.89 ± 0.18 s; drop jump 7.24 ± 1.49 N.Kg, 0.23 ± 0.04 s). Exercises also demonstrated significant differences when compared by movement phase. The highest forces were observed in the impact and landing phases whilst PF within the eccentric and concentric phases being comparable with each other for each given exercise. Impulse was also found to be highly reliable (ICC=0.79-0.97) with large and significant differences (ES=3.6-14.7, $p<0.05$) with values of 2.3-6.0 N.s/kg seen across

exercises in the same ranking order as observed for PF. Furthermore this study provides a novel methodology which describes intensity by movement phase and therefore may provide those concerned with prescribing plyometric programmes with greater insight into the specific biomechanical demands of an exercise. Finally, the present findings provide further support for the use of impulse as a measure of volume for plyometric exercise.

4.3 Introduction

Plyometrics are an established and popular conditioning method, which have been used since the 1960s. Despite this long history of use by high level coaches the approach to programming has changed little in this time. This is typically based around volumes of 30-40 foot contacts per session for high intensity activities such as bounds and drop jumps (Verkoshansky and Siff, 2009, Pfaff, 2010), 100-120 for lower intensity activities such as CMJs and hopping (Potach and Chu, 2000) with recovery periods of 2-3 days often required (Gambetta, 1998).

Highly trained athletes require a precise approach to programming in order to achieve continued improvements in performance. Such an approach to the prescription of exercise necessitates the capacity to quantify all training variables. Volume and intensity are two such variables of primary importance. Volume can be described in a number of ways including the accumulated number of repetitions, total weight lifted (volume load), distance travelled or time spent training (Baechle et al., 2000). The method used is generally dictated by the mode of exercise. With regard to plyometrics the most common practice is the counting of repetitions or foot contacts (Potach and Chu, 2000, Pfaff, 2010, Schexnayder, 2010). Chapter 3 described a system which uses accumulated impulse as a more precise measure of volume; by doing so the coach is able to distinguish between the accumulated work sustained when comparing exercises involving different levels of forces and durations of ground contact rather than treating all repetitions as equal.

The measurement of intensity in plyometrics has been the subject of much enquiry within the literature (Ebben and Jensen, 2002, Ebben et al., 2010a, Ebben et al., 1999, Ebben et al., 2011, Ebben et al., 2008, Jensen and Ebben, 2007, Wallace et al., 2010, Sugisaki et al., 2013, Donoghue et al., 2011). Chapter 3 has demonstrated that PF, taken as the highest force

during ground contact, provides a reliable, valid, and sensitive measure of intensity (Jarvis et al., 2016). When expressed in relative terms this is an easily calculated and understood metric which allows comparison of different plyometric exercises. Consequently it is suggested that this is the preferred method for describing intensity.

A measure of the highest level of mechanical stress an athlete is subjected to must be considered. Accumulated impulse across exercises provides an accurate measure of volume-load. However this can only be considered valid when evaluating tasks involving similar PF; for example, the accumulated impulse during a long distance race would far exceed the mechanical stress which could be tolerated through high force sprinting. Similarly, resistance training sessions of low to moderate loading (≤80% 1-RM, e.g. 30-40 repetitions) are likely to result in greater volume-loads than heavy strength (≥85% 1-RM, e.g. 15-25 repetitions) sessions of lower volume when expressed as volume load (sets x repetitions x load) (McBride et al., 2009). It is perhaps noteworthy that even within such a relatively well defined methodology for describing resistance training volume such as that above the variation in forces and displacement across athletes, exercises, and repetitions should be considered to provide a truly accurate picture of work done.

Empirically, coaches have tended to base assessment of plyometric intensity of an exercise on a subjective view of the level of impact involved (such as that indicated by the box height during a drop jump) (Ebben, 2007). This is consistent with the use of PF as a measure of intensity although landing strategy can alter the PF during depth jumps from the same height (Cappa and Behm, 2013, Jidovtseff et al., 2014b). However this system only provides a ranking of exercises and does not describe the absolute intensity or the magnitude of difference between exercises. Furthermore this subjective approach makes comparisons of intensity between horizontal vs. vertical and unilateral vs. bilateral exercises difficult. Finally, focusing on the task rather than the performance is fundamentally flawed as it fails to factor the athlete's ability to resist yielding during the eccentric phase and produce concentric force during the concentric phase. Consequently the direct measurement of ground reaction force and assessment of PF during these exercises offers the potential to add to the coach's ability to quantify and manipulate the intensity of plyometric exercise when training athletes.

Within Chapter 3, PF was taken as the highest level of GRF throughout a plyometric exercise as previously described by Jensen and Ebben (2007) and Wallace et al. (2010). Whilst such an approach enables distinction between exercises with regard to the highest levels of stress placed on the body of an athlete it does not provide insight as to the nature of this force. An understanding of whether this force has been observed during the impact, eccentric, concentric or landing phases of a jump is likely to prove useful when evaluating how an athlete has achieved a jump performance as well as indicating the potential nature of stress and subsequent adaptation (Cormie et al., 2009, Cormie et al., 2010a, Cormie et al., 2011).

Plyometric GRFs reflect the application of force by the athlete in an attempt to resist yielding and produce concentric force. Subsequently, measures of intensity as represented by PF are likely to be specific to the strength qualities of the population in question, although such considerations are yet to be demonstrated within the literature. These specific neuromuscular qualities are highly developed in elite track and field athletes through a combination of genetic talent and the nature of training regimes (Coh and Mackala, 2013). Therefore the aim of this study was to evaluate the force characteristics demonstrated by elite male track and field athletes during plyometric exercises. Furthermore, PFs during the impact (in plyometric tasks), eccentric, concentric and landing phases of each jump will be evaluated to provide a deeper level of understanding as to the nature of force application. Doing so would provide a new level of insight into the intensity and subsequent training prescription in this population. It was hypothesised that measuring PF and impulse across a range of plyometric exercises would distinguish exercises in terms of intensity and volume-load in an elite male track and field population, as has previously been found in non-elite subjects (Jarvis et al., 2016). It was further hypothesised that the pattern of force application across the four previously identified phases would also distinguish between exercises with greater demands seen in plyometric versus ballistic exercises and in bilateral versus unilateral.

4.4 Methods

4.4.1 Subjects

Ten elite adult male track and field athletes (age 26.9 ± 4.4 years; mass 83.8 ± 5.8 kg; height 188 ± 4.0 cm) volunteered for the study. A consensus definition of elite status does not exist within the literature. This issue has been highlighted and an proposed classification proffered by Swann et al. (2015). This model considers the level of competition, athlete's history of success, experience at the highest level, level of competition within the sport, and global competitiveness within the sport. Each of these categories has 4 levels of classification, ranked from 1-4. The athletes in the present study would be considered in the highest category by at least 80% of the defined criteria. Subjects provided informed consent before participation in the study and ethical approval for the study was obtained through the Institutional Review board.

4.4.2 Test Protocols

Warm-up before the plyometric exercise consisted of a pre-set routine composed of progressive running and jumping exercises (see Table 4-1).

Table 4-1 - Plyometric warm-up routine

Exercise	Sets	Repetitions	Recovery
Jogging	1	400m	Na
Skipping	3	30m each set	Walk back
Strides	3	40m each set	Walk back
Jump to Box (40cm)	3	6	90s
Countermovement Jump	3	6	90s
Rebound Jumps	3	12	90s

This was followed by 3 repetitions of each of the test exercises to provide opportunity for specific warm-up, coached practice and familiarisation. The exercises used for testing were a countermovement jump (CMJ), single-leg CMJ (SL-CMJ), single-leg rebound (RB) and a 40 cm drop jump (DJ) performed in a randomised order (illustrated in **Error! Reference source not found.**). The exercises used are popular training exercises which were intended to provide a

range of intensities as well as utilising differing challenges, namely bilateral vs. unilateral and plyometric vs. ballistic jumps. Furthermore, the subjects were highly familiar with the exercises and routinely use them as part of their training regimes. Three consecutive repetitions of each exercise with minimal rest were performed with three minutes rest between exercises in order to avoid accumulated fatigue. No restrictions were made on arm movements in any of the exercises as subjects were highly trained and able to perform the exercises with a high degree of proficiency and consistency. Subjects were familiar with all of the exercises prior to participation and were supervised and coached by a United Kingdom Strength and Conditioning Association (UKSCA) accredited strength and conditioning coach (ASCC).

Exercise	Start	Mid	End
Countermovement Jump A maximal jump performed rapidly from a standing position			
Drop Jump (40cm) Stepping from a box and rebounding explosively as high as possible with a brief contact time			
Single Leg CMJ As per CMJ but initial stance, propulsion, and landing all performed unilaterally			
Single Leg Rebound Athlete prepares with a single leg CMJ which is immediately followed by a single leg rebound jump on landing			

Figure 4-1 - Description of Exercise Techniques

4.4.3   Equipment

A 60x90cm force platform (Model 9287BA Kistler, Winterthur, Switzerland) mounted within the floor of an athletics venue, sampling at a frequency of 1000 Hz (Owen et al., 2014), was used to measure ground reaction forces during all jumps and was calibrated using calibrated weight lifting plates and zeroed prior to all data collection. Drop jumps were performed using handmade plyometric boxes which were placed alongside, but not on top of, the force platform. The raw vertical force-time data for each jump trial were exported as text files and analysed using a customised Microsoft Excel spreadsheet (version 2016, Microsoft Corp., Redmond, WA, USA).

4.4.4   Data Analysis

Analysis of ground reaction force data was based on the previous work of McMahon et al. (2016) and McMahon et al. (2017a). Velocity of centre of mass (CoM) was calculated by dividing vertical force data (minus BW) by body mass and then integrating the product using the trapezoid rule. Velocity at impact was calculated as described in the equation below where Fz(t) is the vertical ground reaction force, g is the acceleration due to gravity and m is the body mass (Baca, 1999).

$$\text{Vertical landing velocity} = \int_{t0}^{t2}(Fz(t) - mg)dt/m$$

PF was assessed as the highest level of force seen across the time course of each exercise (PF_{whole}) as well as within four specific elements of an exercise, namely; impact (PF_{impact}), eccentric (PF_{ecc}), concentric (PF_{con}) and landing phases (PF_{land}) as defined below. Not all of the exercises included every one of these distinct phases, for example the ballistic exercises (CMJ and SL-CMJ) do not involve an initial impact. It should be noted that the landing phase is described separately within PF_{land} but was not included within the assessment of PF_{whole}. This is based on the fact that this is commonly not regarded as part of the exercise and is therefore rarely coached and highly varied. It is also possible to remove this phase by methods such as jumping onto a raised platform, therefore it is not a fundamental element of the exercise, although does contribute to the additional training stimuli and increased

work. However the value is accounted for when assessing distinct phases of the exercise as this will clearly contribute to the loading stress which an athlete is exposed to. By considering this separately, coaches are better informed as to the consequences of including and coaching a landing phase.

When assessing ballistic exercises (CMJ and SL-CMJ) the onset of movement for each trial was considered to have occurred 30 ms prior to the instant when vertical force had decreased by five times the standard deviation of BW, as derived during the silent period (Owen et al., 2014). The instants of take-off and touchdown were defined as the instants that vertical force had fallen below and above, respectively, a threshold equal to five times the standard deviation of the residual force which was calculated during the first 300 milliseconds of flight phase of the jump (i.e. when the force platform was unloaded) (Moir et al., 2008). The eccentric phase of the CMJ was defined as occurring between the instants of peak negative CoM velocity and zero CoM velocity (McMahon et al., 2017a, McMahon et al., 2016). The concentric phase of the CMJ was deemed to have occurred between the instant that CoM velocity exceeded 0.01 m.s^{-1} and the instant of take-off (McMahon et al., 2017a, McMahon et al., 2016). Interpretation of the phases of the CMJ and SL-CMJ as determined by force-time curves are based on recent work by McMahon et al. (2016) and are illustrated in Figure 4-2.
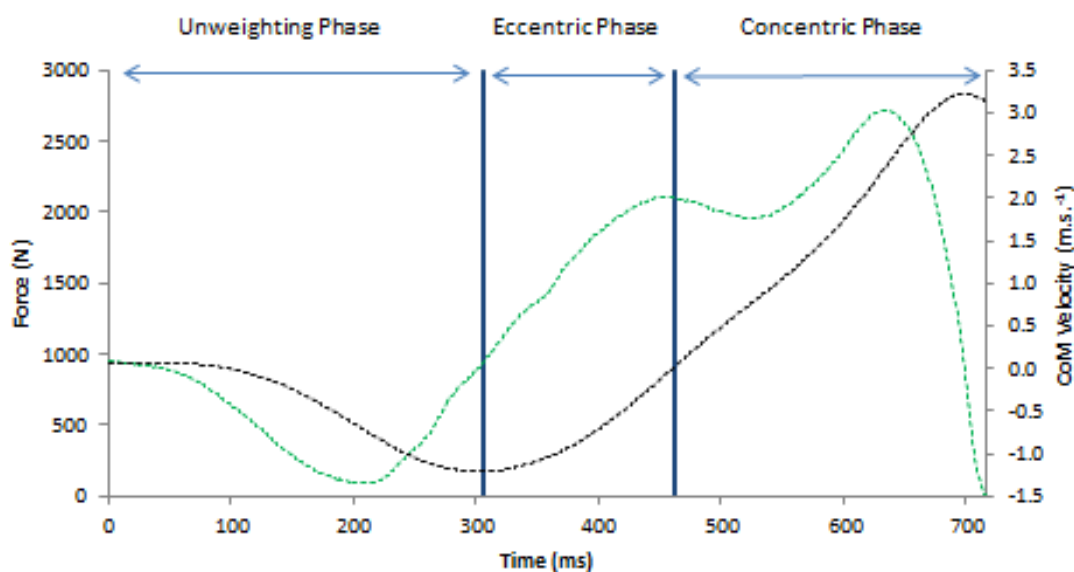
Figure 4-2 - Countermovement jump phase interpretation based on force-time
Green line=force, black line=velocity-time.

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During exercises involving an initial impact (DJ and RB) the instant of touchdown for each exercise was considered to have occurred at the first point at which vertical force exceeded 20 N. This threshold was selected based on the author's experience that such a threshold ensures that residual noise within the system is not incorrectly interpreted as ground contact by the subject. The use of an alternative method to the 5x SD BW used with CMJ was a necessity due to the absence of a standing quiet period on the force platform prior to the jump. The impact peak was taken as the first peak in GRF following the instant of touchdown. The eccentric phase of the jump was defined as occurring between the minimum GRF value following the impact peak and zero CoM velocity. The division of the eccentric phase from the landing phase in this manner was a novel approach as previously no studies within the literature have differentiated in this manner and thus all force prior to the onset of positive movement velocity has been treated as eccentric. The concentric phase of the jump was deemed to have occurred between the instant that CoM velocity exceeded 0.01 m.s^{-1} and the instant of take-off as defined as vertical force falling below 20 N. These phases are illustrated in Figure 4-3.
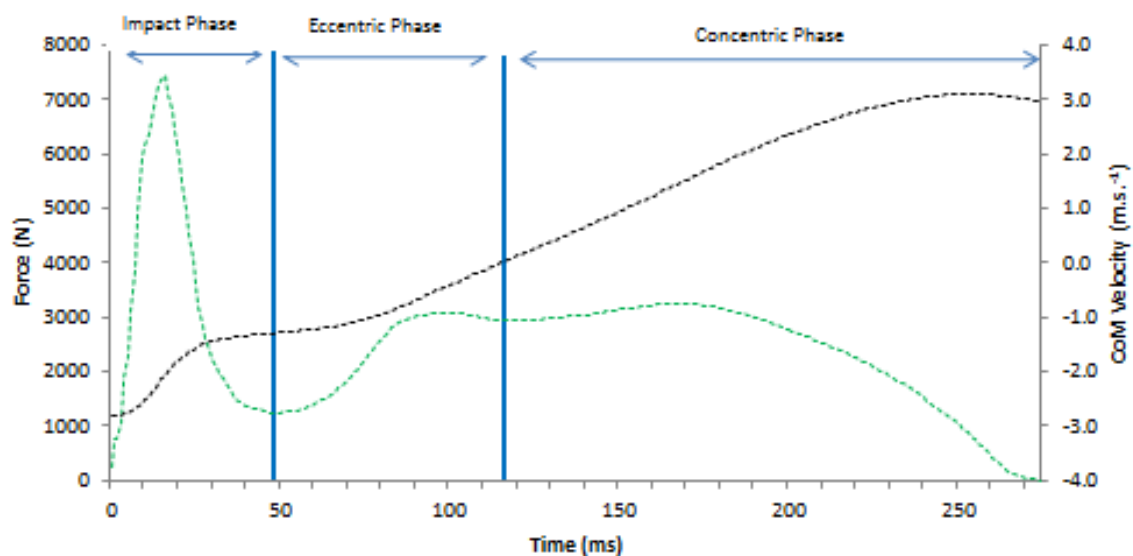
Figure 4-3 - Jump phase interpretation for exercises involving a rebound based on force-time
Green line=force, black line=velocity-time. Example taken from a drop jump exercise.

4.4.5 Statistical Analyses

The statistical analyses were undertaken with SPSS V20.0 for Windows (SPSS, Inc., Chicago, IL). All jump data satisfied parametric assumptions as determined through the Shapiro-Wilk test. Intraclass correlation coefficients (ICCs) were calculated to determine relative reliability between trials for PF and IMP within each exercise which were interpreted as high reliability if r≥ 0.80 (Cortina, 1993). Absolute between-trial variability of each gross variable was calculated using the coefficient of variation (calculated as typical error expressed as a percentage of the mean) expressed as a percentage (%CV). A CV of ≤10% was considered to be reflective of acceptable variability in line with (Cormack et al., 2008). Descriptive statistics (mean ± SD) were computed for these variables. One-way repeated measures analyses of variance using a Tukey post-hoc analysis were performed to test for statistically significant differences between exercises for all variables with exception of peak impact force whereby a paired t-test was used to compare drop jump and single-leg rebound. The level of significance was set at p≤0.05 for all analyses. Statistical power was calculated using G*Power v3.1 (Faul et al., 2009). Cohen's *d* effect size (ES) statistics were conducted to evaluate the magnitude of the difference in exercises according to criterion of > 0.8 large, 0.5–0.8 medium, 0.2–0.5 small (Cohen, 1988).

4.5 Results

All PF variables demonstrated high relative reliability (r ≥0.85). IMP also demonstrated high reliability (r≥0.81), excluding SL-CMJ (r=0.79). Absolute reliability was good within IMP (CV=4.5-9.9) and within PF$_{whole}$ for ballistic exercises (CV: CMJ=4.0, SL-SMJ=9.1), but poor for plyometric exercises (CV: RB=15.7, DJ=20.6) and also poor within movement/contact time for all exercises (CV=17.4-20.2). The poor absolute reliability seen in duration of movement and within the PF of plyometric exercises likely reflects the highly technical nature of these exercises. Statistical power for both PF and IMP was excellent (Power = 1.0).

The mean, SD, CV and ICC of PF$_{whole}$, IMP and movement/contact time values are described in **Error! Reference source not found.** with forces described by movement phase in Table 4-3. Effect sizes and p values are described in Table 4-4, Table 4-5, and Table 4-6. Relative

IMP was significantly different (p<0.001) between all exercises with notably greater IMP achieved during the plyometric (DJ and RB) exercises versus the ballistic (CMJ and SL-CMJ) exercises despite being performed over a much shorter duration. PF$_{whole}$ was also significantly different with large effect sizes in all exercises other than between CMJ versus SL-CMJ. When compared by movement phase, the greatest forces were observed during the impact and landing phases of jumps whereas the eccentric and concentric phases produced significantly lower PF and were of similar magnitude to each other.

Table 4-2 - Mean, SD, CV and ICC values for Impulse, Peak Force (whole movement) and movement/contact time.

Exercise	Relative Peak GRF (N/kg)				Relative Impulse (Ns/kg)				Movement/Contact time (ms)			
	Mean	SD	CV	ICC	Mean	SD	CV	ICC	Mean	SD	CV	ICC
CMJ	2.97*	0.12	4.0	0.88	3.20†	0.25	7.8	0.81	890*	180	20.2	0.96
DJ	7.24†	1.49	20.6	0.91	6.01†	0.27	4.5	0.97	230◊	40	17.4	0.91
SL-CMJ	2.43*	0.22	9.1	0.97	2.33†	0.23	9.9	0.79	940*	180	19.1	0.88
RB	5.21†	0.82	15.7	0.94	4.59†	0.37	8.1	0.97	270◊	50	18.5	0.99

† Significantly different (p < 0.05) from all other exercises
* Significantly different (p < 0.001) from all exercises except CMJ/SL-CMJ
◊ Significantly different (p<001) from all exercises except DJ/RB

Table 4-3 - Mean, SD and ICC values for peak force variables by movement phase.

Exercise	Peak Impact Fz (N/BW)			Peak Ecc Fz (N/BW)			Peak Con Fz (N/BW)			Peak Landing Fz (N/BW)		
	Mean	SD	ICC	Mean	SD	ICC	Mean	SD	ICC	Mean	SD	ICC
CMJ				2.44*	0.31	0.96	2.97◊	0.12	0.88	10.33°	2.56	0.89
DJ	7.24†	1.49	0.91	4.80†	0.72	0.95	4.95†	0.86	0.95	11.02°	2.74	0.94
SL CMJ				1.96*	0.39	0.96	2.43¥	0.22	0.97	5.98†	1.13	0.92
RB	4.86†	0.62	0.85	3.56†	0.58	0.92	3.56°	0.57	0.95			

CMJ=countermovement jump, DJ=drop jump, SL CMJ=single-leg countermovement jump, RB=Single Leg Rebound
† Significantly different (p < 0.05) from all other exercises
* Significantly different (p < 0.001) from all exercises except CMJ/SL-CMJ
◊ Significantly different (p<001) from DJ
¥ Significantly different (p<001) from DJ & RB
° Significantly different (p<001) from DJ &SL CMJ

Table 4-4 - Effect sizes for relative peak force (whole movement) and impulse

Exercise	Relative Peak Force				Relative Impulse			
	CMJ	DJ	SL-CMJ	RB	CMJ	DJ	SL-CMJ	RB
CMJ		4.0	3.0	3.8		10.8	3.6	4.4
DJ	4.0		4.5	1.7	10.8		14.7	4.4
SL-CMJ	3.0	4.5		4.6	3.6	14.7		7.3
RB	3.8	1.7	4.6		4.4	4.4	7.3	

Table 4-5 - Effect sizes for relative peak force by movement phase.

	Peak Impact Force				Peak Eccentric Force			
	CMJ	DJ	SL CMJ	RB	CMJ	DJ	SL CMJ	RB
CMJ						4.3	1.4	2.4
DJ				2.1	4.3		4.9	1.9
SL CMJ					1.4	4.9		3.2
RB		2.1			2.4	1.9	3.2	
	Peak Concentric Force				Peak Landing Force			
	CMJ	DJ	SL CMJ	RB	CMJ	DJ	SL CMJ	RB
CMJ		3.2	3.0	1.4		0.3	2.2	
DJ	3.2		4.0	1.9	0.3		2.4	
SL CMJ	3.0	4.0		2.6	2.2	2.4		
RB	1.4	1.9	2.6					

Table 4-6 - P value comparisons of relative peak force by movement phase.

	Peak Impact Force				Peak Eccentric Force			
	CMJ	DJ	SL CMJ	RB	CMJ	DJ	SL CMJ	RB
CMJ						<0.001	0.181	<0.001
DJ				0.001	<0.001		<0.001	<0.001
SL CMJ					0.181	<0.001		<0.001
RB		0.001			<0.001	<0.001	<0.001	
	Peak Concentric Force				Peak Landing Force			
	CMJ	DJ	SL CMJ	RB	CMJ	DJ	SL CMJ	RB
CMJ		<0.001	0.123	0.071		0.768	0.001	
DJ	<0.001		<0.001	<0.001	0.768		<0.001	
SL CMJ	0.123	<0.001		<0.001	0.001	<0.001		
RB	0.071	<0.001	<0.001					

4.6 Discussion

It was hypothesised that measuring PF and IMP across a range of plyometric exercises would distinguish them in terms of intensity and volume-load within an elite male track and field population. Results demonstrated large significant differences between exercises with the drop jump producing the greatest intensity and volume load. Both the drop jump and the rebound exercise produced greater impulse than the ballistic exercises despite being performed over a much shorter duration. It is notable that within the drop jump athletes produced PF in excess of 7x BW thus justifying the classification of plyometrics as a high intensity mode of exercise. The results found markedly greater intensity in plyometric vs. ballistic exercises and in bilateral vs. unilateral (in absolute terms). These findings are consistent with those in Chapter 3 which found PF to be a sensitive and reliable measure of intensity and the same for IMP as a measure of volume-load. Furthermore the present findings confirmed the hypothesis that assessment of PF by movement phase would distinguish between exercises. The greatest forces were observed during the impact and landing phases which were significantly greater than the eccentric and concentric phases.

Whilst it was not the primary question of this study, possibly the most significant finding is the intensities experienced by elite athletes as described by PF_{whole} in the present study are markedly greater than those demonstrated by recreational athletes in the previous study and within the literature (Wallace et al., 2010, Ball and Scurr, 2009, Jensen and Ebben, 2007, Donoghue et al., 2011). Each of these examples also defined PF as the highest value attained during the plyometric phase (i.e. the entire ground contact excluding the landing phase following the initial jump). The drop jump provides a useful exercise for comparison as it is the most consistently tested. Ball & Scurr (2009) used a 40 cm drop jump which elicited a 4.75xBW PF. A greater height of 46 cm used by Jensen & Ebben (2007) only produced 3.3xBW whereas the 30 cm height used by Wallace et al. (2010) elicited a PF of just 2.9xBW. The previous study within this thesis was consistent with this broad range with a 40 cm drop jump resulting in a PF of 4.4xBW in recreational athletes. Therefore the value of 7.2xBW recorded from a 40 cm drop in the present study represents a marked increase in intensity. The subjects in these studies range from recreational to collegiate level track and field athletes. It appears that the highly elite status of the athletes in the present study

represents a group which cannot be considered homogenous to recreational or intermediate level athletes with regard to plyometric intensity. Consequently the present study provides greater insight into the exercise demands specific to this population.

4.6.1 Peak Force as a Measure of Intensity

Low intensity, high volume, resistance training protocols result in higher total workloads and impulse than are achievable with higher intensity resistance training protocols (Crewther et al., 2008). The same pattern can be seen in running programmes whereby the accumulated training volumes and impulse achieved by an endurance runner would far exceed that of a sprinter. It is clear then that when discussing training volumes as represented by impulse a large degree of homogeneity of PF is required for meaningful comparison. In the present study a 40 cm drop jump produced approximately twice the impulse seen in a CMJ (DJ40 = 6.01±0.27 Ns/kg, CMJ = 3.20±0.25 Ns/kg). Consequently two CMJs would typically represent a similar total training impulse as one DJ. However, such a comparison may be overly simplistic when PF is considered. The relatively low bilateral PF associated with CMJ (2.97±0.12 N/kg) can be compared with running unilateral GRFs and thus this level of force can demonstrably be tolerated in relatively large volumes without undue stress on the athlete (Nilsson and Thorstensson, 1989). However the high forces seen in the present study during the DJ (7.2±1.5 N/kg) represent a significant stress. This is reflected in the fact that volumes as low as 20-50 repetitions per session of this type of work are commonly prescribed (Potach and Chu, 2000).

Evaluation of the timing of force application during which impulse is accumulated further illustrates the need to consider the magnitude of forces. Within the present study ballistic exercises involved an application of force over a time period approximately 3-fold longer than plyometric exercises (SL-CMJ and CMJ=0.89-0.94 s; DJ and Rebounds = 0.24-0.27 s). When considered alongside IMP values approximately 2-fold greater over a far shorter window it is clear that the nature of mechanical stress incurred is very different across these exercise classifications. Consequently, whilst impulse remains a valid and reliable method of quantifying volume of plyometric and ballistic volume, comparisons should only be made between exercises with similar PF characteristics. In practical terms, it may be that some

form of exercise banding would provide a useful framework for the structure of training and the manipulation of volume. It should be noted that the lower PF across exercises in sub-elite populations results in smaller PF differences between exercises and therefore comparison may remain valid (Jarvis et al., 2016).

It is clear that the use of a plyometric challenge involving an impact offers the potential to apply a greater load to the body in comparison with a ballistic challenge such as a CMJ. This is demonstrated by the greater PF seen in plyometric versus ballistic exercises. Analysis of the concentric phase also demonstrates an augmented level of force production following the stretch shortening cycle. Consequently, in this population, plyometric exercises can be considered to add load both through the rebound impact and an enhanced concentric phase.

It is noteworthy that whilst elite athletes demonstrated greater mean impulse in comparison with the same exercises performed by recreational athletes in the previous study, impulse differences were less than PF differences. For example in a 40cm DJ PF was 64% greater (recreational = 4.4±0.18N/kg, elite=7.2±1.5 N/kg) whereas impulse was only 19% greater (recreational = 5.13±0.30 Ns/kg, elite=6.01±0.27 Ns/kg). This reflects the fact that the elite group produced greater forces over a shorter time frame. Once again this illustrates the important point that impulse may be considered time-dominant or force-dominant and may be misleading if used to represent the stimulus on the athlete without consideration of the time frame over which the impulse was accumulated or the PF involved.

Typically the programming focus of coaches is placed on the active component of an exercise, such as the propulsion phase of a CMJ. The PF data from both this and the previous study demonstrate that the magnitude of force is far greater during a plyometric exercise when compared with a ballistic exercise due to the rebound impact. However analysis of jump phases demonstrates that the landing component represents a far greater level of force which is rarely considered in programming. Consequently the landing phase of a CMJ is responsible for far more of the session volume loading experienced by an athlete than the jump itself. A similar scenario exists for drop jumps during which there are actually two impacts to be absorbed (i.e. the rebound impact and subsequent landing impact) rather

than the singular contact which would be factored into the traditional coaching approach. This additional load can of course be removed or moderated by jumping onto a platform such as a box. The inclusion or removal of such a platform will have a profound effect on the total mechanical stress. Therefore, to land or not-to-land should be regarded as a key consideration during session planning. It is for this reason that the methodology of this study did not include $PF_{landing}$ within PF_{whole} in order that practitioners are able to consider the fundamental characteristics of the exercise in isolation from this discretionary element.

4.6.2 Comparisons by Movement Phase

The assessment of intensity through analysis of PF by movement phase is a novel aspect of this study which has not been reported within the literature previously. These findings confirmed the hypothesis that assessment of PF by movement phase would enable distinction between exercises. The quality and consistency of execution of these exercises can be considered high in this group of highly trained subjects. This is likely to have contributed to the statistical differences between exercises. It remains to be seen if the same distinctions are evident in less well trained populations.

The distinction between the impact and eccentric phases raises questions as to the nature of loading within each phase and the likely adaptations. This is highlighted by the comparison of PF_{impact} and PF_{ecc} in DJ which found very high forces in the former compared with the latter. Critical to coaches will be the question of what potential differences this may make to stimulus and adaptation. The present study does not enable us to answer this question but it is likely that kinematics must be considered as key here. It is reasonable to assume that during an impact phase which is executed in an "athletic position", i.e. one in which there is moderate flexion of hips, knees, and ankles, that much of the impact force will be placed on the MTU of these major joints. Provided that healthy alignment of these joints is maintained, this may be considered a positive training stress given that these structures are primary targets of plyometric and ballistic exercise (Couppe et al., 2008, Foure et al., 2012, Foure et al., 2009, Foure et al., 2011). However, if high impact forces are a result of kinematics characterised by an upright posture with minimal joint flexion there is likely to be a high loading on the skeletal system which may be considered undesirable and

potentially injurious (Moritz and Farley, 2005). Athletes within the present study demonstrated an "athletic position" in landing and thus the high forces demonstrated can be assumed to be largely the result of neuromuscular ability to maintain joint stiffness. An understanding of this concept is critical as the highest loadings in all exercises were seen in the impact and landing phases rather than the eccentric and concentric phases which are likely to be the primary target. Particularly in the case of the ballistic exercises, the inclusion or removal of a landing phase has major implications on the total force which the athlete must tolerate. A considered view as to whether load stress in this phase contributes to training adaptations and the likelihood of increased injury risk are crucial to informing how exercises may be performed.

Whilst PF_{whole} can be evaluated within a training session relatively simply (where force platform technology is available), evaluation of PF by phase is more challenging and unlikely to be achievable within an applied setting due to the processing required. It is noted that during the period of study for this thesis, commercial software capable of providing this type of automated analysis has become available. However, accurate identification of specific phases of movement is not achievable via the methods used in the present study when the drop height of the athlete's CoM is not known. This is required in order to estimate velocity and displacement of CoM so that phases can be identified. Accurate estimating of drop height is challenging in a number of plyometric exercises. Consequently the findings of the present study may be best used as a reference to guide coaches as to likely force application patterns within these exercises. However, this should only ever be considered a guide and the potential for individuals to apply force through differing patterns should not be overlooked.

4.6.3   Comparisons Across Exercise Classifications

As hypothesised, the greatest forces were observed during plyometric exercises in comparison with ballistic exercises and that the highest forces occurred during the impact and landing phases. It is perhaps more notable that the plyometric exercises also demonstrated significantly greater forces during the eccentric and concentric phases of movement. Such an observation demonstrates the capacity of the subjects to utilise the SSC

opportunity presented by the rebound to augment the eccentric and concentric phases of the jump.

A key challenge to coaches seeking to plan manipulations in volume and intensity comes from the difficulty in comparing exercises which differ in mechanical nature such as unilateral versus bilateral movements. During the previous study it was suggested that a weighting factor of 1.21 be applied to unilateral forces in order to make comparison with bilateral tasks. This is based on a theory of body segment contributions (Graham-Smith et al., 2015). The PF_{ecc} and PF_{con} of CMJ versus SL-CMJ were greater by a factor of 1.24 and 1.22 respectively. This supports the validity of this weighting factor and suggests that the relative intensity of CMJ and SL-CMJ may be similar despite the absolute differences in force. The same phases of the plyometric exercises (DJ and RB) were greater by a factor of 1.35 and 1.39 respectively, possibly suggesting that the bilateral movements are of greater relative intensity when segmental contributions are considered. This supports this novel approach to comparing unilateral and bilateral exercise although further research is required to validate the method.

4.6.4   Practical Applications

To date, exercise training literature does not typically differentiate between the performance level of athlete when discussing plyometric intensity. It has been recommended that elite athletes may tolerate greater volumes of work than novice athletes (Potach and Chu, 2000). Exercises such as those used in the present study are classified as high stress exercises which require 2-3 days recovery (Gambetta, 1998).

Previous studies have found relative PFs in plyometric exercises to be in the region of 3-4 times BW (Wallace et al., 2010, Ball and Scurr, 2009, Jensen and Ebben, 2007, Jarvis et al., 2016). These bilateral forces are comparable with the unilateral forces experienced during running (Nilsson and Thorstensson, 1989). As a result they most likely do not merit the classification of high stress exercises in non-elite populations. During the present study elite athletes produced forces in the order of 7x BW in bilateral plyometric challenges and 5x BW in unilateral plyometric tasks. These stark differences between populations demonstrate

that the historical approach of categorising exercise intensities regardless of the level of athlete may be flawed.

The present results may be contrary to popular recommendations that novice athletes should perform lower volumes of work than elite counterparts (Potach and Chu, 2000). The relative intensity appears to be far higher in elite athletes in the present study in comparison with values reported within the literature (Jensen and Ebben, 2007, Wallace et al., 2010) and those observed in Chapter 3, therefore sessions which are matched in terms of contacts will differ greatly in terms of the mechanical stress accumulated and may prove more stressful for elite athletes. Under such circumstance it is reasonable to conclude that in fact the elite athlete should perform lower volumes than their recreational counterpart. Further research is required to explore the effects of contact matched sessions between elite and non-elite athletes on markers of fatigue and stress.

Resistance training exercises are typically described by the nature of the task, i.e. the load lifted multiplied by the number of repetitions. Despite the apparent logic of this system there may be significant variance between lifts of equal weight in terms time under tension and the subsequent implications on neuromuscular fatigue although total work performed appears to remain constant provided that range of motion does not vary (Tran and Docherty, 2006, McBride et al., 2009). When compared with results from the Chapter 3, the present findings demonstrate that athletes performing an identical plyometric task, such as completing a 40 cm drop jump, can produce significantly different outcomes when the populations are heterogeneous. Successful performance of jumping tasks demands both the skilful application of force as well as the underpinning strength qualities, both of which combine to determine joint stiffness to resist yielding on impact and to produce concentric force. Consequently, plyometric exercise intensity may be best classified by the outcome in the form of PF rather than the task itself. The trend of exercise intensity appears similar in this and the previous study, illustrating that the nature of the task does contribute to the potential for high forces to be applied. Therefore it appears legitimate to describe an exercise as having an "intensity opportunity". This refers to the fact that certain exercises, such as progressively higher drop jumps, may present the athlete with an opportunity to use the impact to produce a greater PF. This is most likely to be observed during the impact and eccentric phases although successful augmentation of these phases may provide the

opportunity for an augmented concentric phase through the increased utilisation of elastic energy and greater active state. However, taking advantage of this opportunity is dependent on the athlete's ability to resist yielding and avoid dissipating increased forces which naturally follow increased falling velocity from greater drop heights.

Further to the requirement to differentiate exercise intensity between populations, high level programming may necessitate a differentiation between athletes within a population. Plyometric exercises involve a large skill component due to the rapid and complex multi-joint actions involved. Therefore the importance of motor specificity means that an athlete may demonstrate varied levels of competency across differing motor tasks (Nakata et al., 2010, Sale, 1988). The influence of motor skill means that training history and personal preferences are amongst a number of factors which dictate that the exercises in which an athlete shows the most skill will vary significantly (Eloranta, 2003). Furthermore, the nature of the exercise will also change the emphasis of the strength quality required to underpin performance. For example, a CMJ relies primarily on concentric strength during the concentric phase whereas reactive strength becomes more prominent in tasks such as drop jumping (Moritani, 1993, Earp et al., 2010, Earp et al., 2011, Beattie et al., 2017). This is further evidence that the historical approach within the literature to place an intensity rating on an exercise per se is highly flawed.

Naturally, with increased joint stiffness comes increased PF which the athlete must tolerate. The potential performance augmentation this increased intensity may offer must be reconciled with a greater systemic stress to the athlete and associated injury risk. This is in contrast to the objective of improving landing mechanics to reduce injury risk. In the latter scenario the reduction of impact force is desirable in order to decrease injury risk (Hewett et al., 2005a, Bates et al., 2013).

In Chapter 3 sEMG was used to classify exercises as ballistic or plyometric. Whilst elite athletes in the present study exhibited greater forces during the ballistic CMJ and SL-CMJ when compared to the non-elite athletes studied in Chapter 3, the magnitude of difference is much smaller than during plyometric comparisons. Therefore it would appear that it is the ability to generate force through elastic energy, underpinned by an ability to resist yielding

through isometric and eccentric strength, which is the dominant source of greater intensity in elite populations as opposed to concentric force.

4.7 Limitations

The training background of the elite athletes within the present study are relatively homogenous, i.e. horizontal and vertical jumpers. This provides a reliable picture of this discrete population, however it is important to consider potential differences with other discrete groups who may also be described as elite athletes such as sprinters, middle distance runners and team sports athletes.

The assessment of reliability in this study is restricted to within session reliability rather than between session reliability. The rationale for this is the intention to demonstrate the capacity of variables to distinguish between exercises rather than of the athlete to reproduce consistent measures. Future studies applying this assessment system to monitor an athlete or group of athletes will require an understanding of between session reliability in order to evaluate meaningful differences.

4.8 Summary

The results of the present study provide unique and novel insight into the demands of plyometric and ballistic exercise within elite track and field athletes. Furthermore the findings describe a novel approach to analysing the demands of jump exercises by movement phase, thus providing a greater level of insight into the specific nature of stimulus. Exercise guidelines for this population may be informed by these findings and will allow coaches and athletes to prescribe training regimes with a greater degree of precision and clarity of likely stimulus.

It is also clear that a given plyometric exercise cannot be considered to have an inherent, fixed intensity. Instead it may only be regarded as having an "intensity opportunity" with the actual outcome being dependent on the fixed characteristics of the exercise and the variable neuromuscular qualities of the athlete performing it. Indeed, intensity opportunity can be considered both population specific and influenced by the skill and strength qualities

of the athlete within a given population. The large forces observed during the landing phase of ballistic exercises highlights that coaches should give keen consideration to the total number and intensity of the landings accumulated within a session in contrast to the traditional view of simply counting impacts preceding a propulsion. Finally, whilst the absolute intensity of an exercise may vary between populations the present results demonstrate the capacity of plyometric exercises to elicit greater intensities than ballistic exercises during impact, eccentric and concentric phases and well as greater volume-loads for a single repetition as represented by impulse. Comparisons of bilateral and unilateral exercises are less clear owing to the absence of an accepted methodology for relative comparisons.

Having established and applied a methodology for evaluation of the magnitude of stimulus during jumping exercises, the focus of this thesis will now turn towards recent interest in the exploration of kinetic and kinematic characteristics which support elite jump performance.

Chapter 5 – A Comparison of Countermovement Jump Phase Characteristics Between Elite Jumping Athletes, Professional Rugby Players and Recreational Athletes.

5.1 Overview

Previous chapters within this thesis have explored differing methodologies for quantifying intensity of ballistic and plyometric exercises and subsequently applied these findings to assessing the performances of elite athletes in respect to exercise intensity. The present chapter will extend this enquiry by exploring the kinetic signatures of different athletic populations, achieved during a countermovement jump (CMJ), through temporal phase analysis. The study will compare three groups with differing training backgrounds to identify points of difference in their CMJ characteristics. In doing so it may be possible to gain insight into the nature of optimal performance which would subsequently inform training strategies for those wishing to augment and optimise jump performance.

5.2 Abstract

The purpose of this study was to compare the kinetic and kinematic jump characteristics of three distinct populations with a view to identifying characteristics which support elite performance through the application of a novel methodology. Elite jumping athletes (EJ), professional rugby league (RL) and recreational athletes (REC) performed maximal CMJs on a force platform with ground reaction forces collected and analysed using a temporal phase analysis (TPA). Nineteen force derivative variables were compared between groups as well as force-, power-, velocity-, displacement-time, and force-velocity curves through TPA. EJ achieved greater jump heights and modified reactive strength index (RSI-mod) scores than RL who in-turn outperformed REC (Jump height: EJ=0.50±0.06 m, RL=0.37±0.05 m, REC=0.30±0.04 m; RSI-mod; EJ=0.66±0.17, RL=0.47±0.11, REC=0.41±0.06) thus providing a basis for identifying those factors underpinning greater performance. Kinetic assessment suggests that superior performance was largely the result of a greater concentric impulse and greater mean and peak power during the concentric phase. TPA revealed EJ and RL

demonstrating a different kinematic model to REC characterised by greater CoM displacement during unweighting (eccentric displacement: EJ=0.37±0.10 m, RL=0.34±0.04 m, REC=0.27±0.06 m) with a moderate but not significant increase in eccentric phase duration (eccentric phase duration: EJ=0.18±0.06 s, RL=0.17±0.04 s, REC=0.15±0.03 s). This resulted in greater eccentric impulse and a longer concentric phase with large subsequent increases in concentric impulse. EJ and RL were differentiated by the capacity of EL to produce power during the concentric phase. These results demonstrate that enhanced CMJ performance may be achieved through the adoption of an alternative kinematic model with greater negative CoM displacement as well as through superior neuromuscular capability.

5.3 Introduction

Recently the use of temporal phase analysis (TPA) has provided new insight into the kinetic characteristics of the CMJ (Cormie et al., 2009, Cormie et al., 2008, Cormie et al., 2010b, Gathercole et al., 2015a, Gathercole et al., 2015c). This methodology illustrates the pattern in which force, power, velocity and displacement vary throughout a jump and within specific phases of movement and therefore offers insights into how 'good' jumpers achieve high levels of performance. Key studies within this field are reviewed in section 2.4.

The TPA methodology was first used to assess CMJ performance by Cormie et al. (2008). Whilst the trialling of the methodology was not the primary focus of the investigation, this led to a number of subsequent studies which sought to exploit the opportunity to explore differences in kinematic characteristics across different groups.

Cormie et al. (2009) conducted a cross-sectional comparison of experienced jumpers (CMJ >0.5 m) with non-jumpers (CMJ <0.5 m). They found that experienced jumpers achieved superior jump performances which were attributed to physiological superiority as represented by the greater strength levels. The utility of the TPA methodology was demonstrated through insights into differences between groups at specific time points (between 0-100% of the normalised movement time). Within the same paper as the cross-sectional study, Cormie et al. (2009) conducted a longitudinal comparison during which subjects were assigned to a training (12 weeks of power training) or control group.

Following the training period subjects exhibited altered CMJ mechanics characterised by a greater depth of descent. Notably this was achieved without increasing the duration of the eccentric phase and consequently eccentric power, force and velocity were all greater following training. This increased emphasis on the eccentric phase altered the shape of the force-time curve which saw the establishment of a bimodal force tracing with an enhanced eccentric peak followed by a drop in force and a subsequent concentric peak (see Figure 5-1 as an example bimodal force trace). These findings offered valuable new insight into the mechanisms underpinning enhanced performance following training.

The finding of an augmented CMJ eccentric phase being a critical adaptation to training was supported by Cormie et al. (2010b). Following a 10-week training programme subjects demonstrated increases in CMJ height as well as peak eccentric power, peak eccentric force, and peak eccentric-RFD. The authors suggest that this model of adaptation represents a more mechanically efficient jump strategy following training which presents a greater opportunity for elastic recoil (via SEC and PEC) and potentiation of the muscle spindle (Turner, 2010) following the increased eccentric loading. This and the previously discussed studies led to a novel insight into an adaptation to training which is characterised by a more effective use of force through the loading of the eccentric phase.

Having established TPA as a valid and informative method of analysis alongside greater insight into effective models of jumping and adaptations to training, the focus within the literature has turned toward comparison of heterogeneous groups. McMahon et al. (2016) compared CMJ performance of senior male rugby players with academy players. Senior players achieved superior jump height to academy players as well as greater RSI-mod scores. Senior players demonstrated greater relative eccentric and concentric impulse. However, the superior performance was not accompanied by significantly greater peak eccentric force nor were there any significant differences in either relative eccentric or concentric force during the TPA. This illustrates the important point that, whist peak forces may be useful with regard to describing intensity (i.e. the highest level of stress involved in a movement) impulse is the most important metric when determining the outcome of a jump.

McMahon et al. (2017a) conducted a comparison involving groups differing in both sex and sporting background. CMJ performance, assessed via TPA, was compared across the groups with male rugby players jumping higher than the female netball players. No significant differences were observed in either the relative PF or the force-time signatures of the two groups. However an alternative movement pattern was observed characterised by a greater depth of descent during the eccentric phase by the men. These results demonstrate the need for further comparisons of differing populations as well as the value of a more in-depth assessment of the kinetic and kinematic profile beyond peak and mean measures.

Sole et al. (2017) adopted an approach which may provide a stronger basis for cross-group comparisons by assessing CMJ performance in collegiate athletes (75 male, 75 female). Subjects were ranked by jump height and the top, middle and bottom 15 jumpers of each sex were taken forward for further analysis. Comparisons indicated that higher jumpers exhibited larger relative force and impulse during the concentric phase of the CMJ. This methodological approach represents a robust method for the evaluation of characteristics which underpin jump performance.

Athletes have also been grouped according to jumping ability by McMahon et al. (2017b) although in this instance jumpers were classified according to RSI-mod score rather than jump height. Superior jumpers demonstrated a more rapid unweighting phase and increased peak eccentric power and peak eccentric force. These results replicate previous findings of the potential to enhance CMJ performance through an augmented eccentric phase.

There is an emerging body of enquiry within the literature which uses a TPA approach to gain insight into the nature of force application beyond peak values (Cormie et al., 2009, Cormie et al., 2008, Cormie et al., 2010b, Gathercole et al., 2015a, Gathercole et al., 2015c, McMahon et al., 2017a, McMahon et al., 2017b, McMahon et al., 2016). Such enquiry provides novel insight into the kinematic and kinetic characteristics of elite performance, the adaptations to training and the markers which best identify neuromuscular fatigue. Recent research has proposed two alternative models of achieving superior jump performance; one which is based on greater force production during the concentric phase through strength advantage, another through an augmented eccentric phase following

training adaptations (Cormie et al., 2009). This study extends this enquiry to compare ballistic jump characteristics across 3 discrete groups of athlete: elite jumpers, professional rugby players, and recreational athletes using a TPA methodology.

The aim of this study was to compare elite jumpers, professional rugby players, and recreational athletes to explore differences which may illustrate the specific kinetic and kinematic characteristics which underpin elite performance. Professional rugby players provide a useful comparison with elite jumpers as they can be considered elite athletes in comparison with recreational subjects but may lack both the genetic make-up and training background typical of elite jumpers. It was hypothesised that elite jump athletes would achieve greater jump heights compared to professional rugby players who in turn would out-perform recreational athletes. It is further hypothesised that the superior jump height would be achieved through a model of force application characterised by greater eccentric force and impulse as a precursor to greater concentric impulse as seen in previous studies Finally, it was hypothesised that TPA would reveal differences in the kinetic and kinematic characteristics of groups to explain differences in performance.

5.4 Methods

5.4.1 Subjects

Eleven adult male elite jump (EJ) athletes (age 24.5±3.8 years; mass 79.6±6.8 kg; height=1.88±0.04 m) competitive at national and international level athletics, 12 male professional rugby league (RL) players (age 25.3±5.0 years; mass 93.6±8.7 kg; height=1.84±0.01 m), and 12 male recreational (REC) athletes (age 20.1±3.5 years; mass 76.1±12.2 kg; height=1.74±0.05 m) who participated in collegiate level sport volunteered for the study. The elite status of EJ and RL is described in more detail in Table 5-1 based on the model proposed by Swann et al. (2015). All subjects provided informed consent before participation and ethical approval for the study was obtained through the Institutional Review board.

Table 5-1 - Elite Athlete Classification Ratings

Variable	Rating (1-4)	
	Jump Athletes	Rugby League Players
Athlete standard of performance	3-4 (national & international level)	4 (top tier professional league)
Athlete success	3 (infrequent success at international level)	3 (infrequent success at top tier)
Experience at highest level	3 (5-8 years)	3 (5-8 years)
National competitiveness of sport	4 (National sport, large sporting nation)	3 (sport ranks in top 5 in country)
Global competitiveness of sport	4 (Regular Olympic sport with major international competition)	2 (world championships limited to a few countries)

Based on (Swann et al., 2015)

5.4.2 Testing

Immediately prior to testing all subjects completed a supervised dynamic warm-up, which included running, jumping and mobility exercises (as described previously in Table 4-1). Following warm-up, the test protocol required subjects to perform two maximal CMJs to self-selected depth with a brief pause between each repetition to regain composure. A simple instruction to jump as high and fast as possible with hands on hips was given prior to performing the jumps. A stationary silent period was required prior to performing each jump. The rugby players and recreational athletes performed the testing at a university biomechanics laboratory using a Kistler type 9286AA force platform sampling at 1000 Hz. For practical reasons the elite jumpers performed the testing at an athletics venue using a Kistler Model 9287BA, platform. Ground reaction force-time data for all groups was captured using Bioware 5.11 software (Kistler Instruments Inc., Amherst, NY, USA). The raw vertical force-time data for each jump trial were exported as text files and analysed using a customised Microsoft Excel spreadsheet (version 2016, Microsoft Corp., Redmond, WA, USA).

5.4.3 Data Analysis

Analysis of ground reaction force data was based on the previous work of McMahon et al. (2016, 2017a). Centre of mass (CoM) velocity was calculated as described in the previous chapter. Power was calculated by multiplying vertical force and velocity data at each time point. CoM displacement was determined by double integration of the vertical force data.

The phases of movement were defined as described for CMJ and SL-CMJ in the previous chapter. These are illustrated in Figure 5-1.
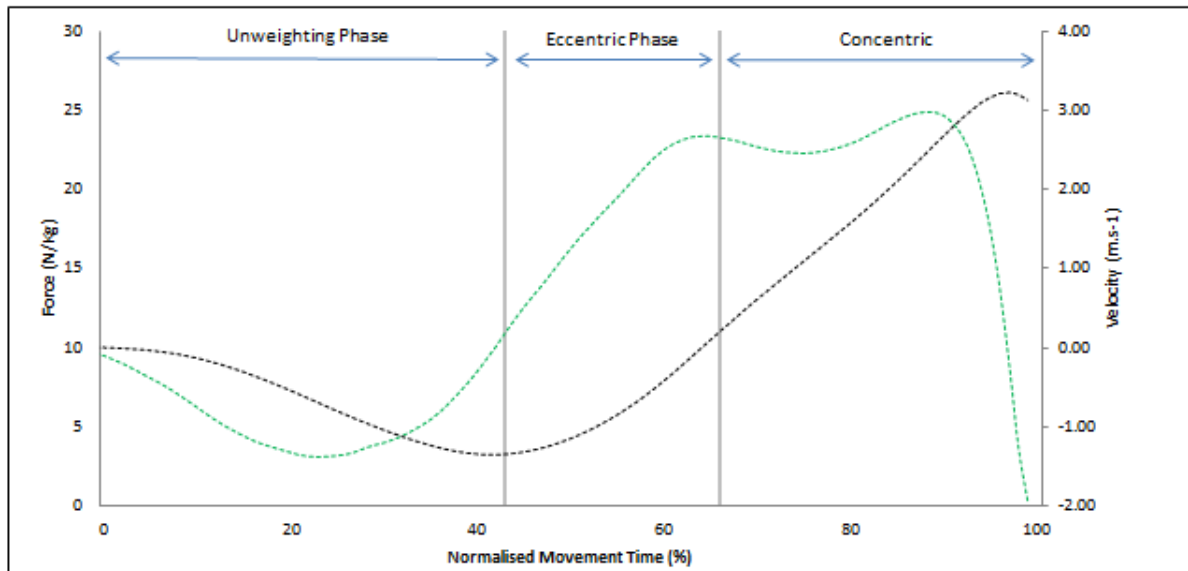
Figure 5-1 - Countermovement jump phase interpretation based on force-time
Green line=force-time curve data, black line=velocity-time curve data (data represents the pooled mean of jumpers' force- and velocity-time curves).

Having calculated velocity and power as described above and identified the specific phases of the jump performance variables were calculated as described in Table 5-2. All kinetic data were divided by body mass to enable comparison across groups.

Table 5-2- Calculation of CMJ performance variables derived from force-time data.

Variable	Units	Calculation Method
Jump height	m	Take off velocity^2/(2x9.81) (Moir, 2008)
RSI-mod	-	Jump height divided by movement time (McMahon et al., 2017b)
Ecc Peak Force	N	Maximum value attained during the eccentric phase of the jump
Con Peak Force	N	Maximum value attained during the concentric phase of the jump
Mean Ecc Force	N	Mean value attained during the eccentric phase of the jump
Mean Con Force	N	Mean value attained during the concentric phase of the jump
Leg stiffness	N.kg.m^{-1}	Ratio between peak eccentric force and eccentric COM displacement
Ecc Impulse	N.s	Area under net force-time curve (minus BW) using trapezoid rule (Kirby et al., 2011)
Con Impulse	N.s	
Peak Ecc Power	W	Max. value during eccentric phase (force x velocity at each time point)
Peak Con Power	W	Max. value during concentric phase (force x velocity at each time point)
Mean Ecc Power	W	Mean value attained during the eccentric phase of the jump
Mean Con Power	W	Mean value attained during the concentric phase of the jump
Peak Ecc Velocity	m.s^{-1}	Maximum value attained during the eccentric phase of the jump
Peak Con Velocity	m.s^{-1}	Maximum value attained during the concentric phase of the jump
Mean Ecc Velocity	m.s^{-1}	Mean value attained during the eccentric phase of the jump
Mean Con Velocity	m.s^{-1}	Mean value attained during the concentric phase of the jump
Area under FV-curve	W	Onset of movement to the instant of take-off using Simpson's rule (Cormie et al., 2008)
Mean Ecc-RFD		Ecc PF divided by time taken to reach this value from the onset of the eccentric phase (McMahon et al., 2017a)

CMJ data were also analysed using a TPA as described previously within the literature (Cormie et al., 2008, McMahon et al., 2017a, McMahon et al., 2016). Each subject's force-, velocity-, power- and displacement-time curves were modified from the onset of movement to the instant of take-off to equal 500 samples. The time delta between the original samples was changed (i.e. original number of samples/500) and was subsequently re-sampled. This resulted in an average sample frequency of 650±128 Hz EJ, 633±69 Hz for RL and 687±93 Hz for REC. This process allows the averaged curve of each variable to be expressed over a percentage of time (i.e. 0-100% of movement time).

5.4.4 Statistical Analyses

The statistical analyses were undertaken with SPSS V23.0 for Windows (SPSS, Inc., Chicago, IL). All jump data satisfied parametric assumptions as determined through the Shapiro-Wilk test. A two-way random-effects model intraclass correlation coefficient (ICC) was used to

determine the relative between-trial reliability of each variable pooled across the three subject groups. ICC values ≥ 0.80 were interpreted as being highly reliable (Cortina, 1993). Absolute between-trial variability of each variable was calculated using the coefficient of variation expressed as a percentage (%CV) with CV <10% considered acceptable (Cormack et al., 2008).

The means of the two CMJs performed for each variable were compared between groups as this has previously demonstrated greater reliability than comparisons of peak values (Gathercole et al., 2015b). A one-way ANOVA was used to compare means between groups with the alpha level set at p<0.05 with a Tukey post-hoc analysis. Cohen's *d* effect size (ES) statistics were conducted to evaluate the magnitude of the difference in means according to criterion of > 0.8 large, 0.5–0.8 moderate, 0.2–0.5 small, <0.2 trivial (Cohen, 1988).

Differences in force-, velocity-, power-, and displacement-time curves were determined by plotting the time-normalized average curves for each group along with the corresponding upper and lower 95% confidence intervals (CI) to create upper and lower control limits and identifying non-overlapping areas.

5.5 Results

All variables showed good between-trial reliability (ICC=0.84-0.99) and acceptable between-trial variability (CV=1.7-9.9) with the exception of leg stiffness (CV=14.4), and Ecc-RFD (CV=13.2). Comparisons of anthropometric means revealed significant differences between groups with RL being heavier than both other groups (p=0.001-0.008, ES=1.6-3.1) and REC being shorter than both other groups (p<0.001, ES=1.7-1.8). Descriptive statistics for all performance variables are described in Table 5-3. EJ achieved greater jump heights and RSI-mod scores than RL who in-turn outperformed REC. These performances were achieved without significant differences in peak eccentric or concentric force across groups. REC demonstrated a stiffer countermovement technique in comparison with both other groups. Superior CMJ performance appears to be underpinned by large differences between groups within the concentric phase of jumping as demonstrated by greater concentric impulse,

mean and peak concentric power. Statistical analysis of between group comparisons are described in Table 5-4.

Table 5-3 - Descriptive statistics of CMJ variables.

Jump Variable	EJ			RL			REC			
	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV	ICC
Jump Height (m)	0.50†	0.06	3.5	0.37*	0.05	2.7	0.30	0.04	2.2	0.99
RSImod	0.66†	0.17	6.4	0.47	0.11	4.9	0.41	0.06	2.9	0.98
Peak Ecc Fz (N.kg)	23.93	3.12	4.3	24.38	4.29	3.7	24.39	2.46	4.1	0.93
Peak Con Fz (N.kg)	26.63	2.45	4.3	25.25	3.17	2.6	25.26	2.71	3.2	0.91
Leg Stiffness (N.kg.m^{-1})	1.24	0.52	14.4	1.09	0.37	11.7	1.87†	0.82	13.0	0.87
Eccentric Impulse (N.s.kg)	1.40	0.23	6.4	1.37	0.28	3.9	1.18	0.19	4.4	0.95
Concentric Impulse (N.s.kg)	3.14†	0.18	1.7	2.68*	0.20	1.4	2.42	0.16	1.1	0.99
Eccentric RFD (N.s^{-1}.kg)	85.61	34.50	13.2	95.15	42.38	12.6	105.17	38.03	13.0	0.89
Peak Eccentric Power (W.kg)	-20.25	4.92	-9.9	-20.77	7.76	-6.5	-16.79	4.04	-6.8	0.93
Peak Concentric Power (W.kg)	69.02†	7.44	3.4	53.28	6.71	1.6	48.22	3.95	2.2	0.98
Eccentric Phase Time (s)	0.18	0.06	6.7	0.17	0.04	6.9	0.15	0.03	7.6	0.93
Concentric Phase Time (s)	0.27	0.05	5.3	0.27	0.03	2.9	0.24	0.03	3.4	0.94
Movement Time (s)	0.80	0.16	4.3	0.80	0.10	2.8	0.74	0.10	4.2	0.94
Mean Ecc Fz (N.kg)	18.16	2.54	3.5	18.49	3.16	3.5	18.07	1.97	4.0	0.93
Mean Con Fz (N.kg)	21.51	2.15	3.1	19.72	1.79	1.7	19.93	1.27	1.7	0.94
Mean Ecc Power (W.kg)	-14.81	3.37	-9.1	-14.88	4.89	-5.5	-12.50	2.76	-6.0	0.95
Mean Con Power (W.kg)	35.94†	4.81	4.4	29.86	4.81	2.6	27.53	2.21	1.9	0.97
Mean Ecc Velocity (m.s^{-1})	-0.91	0.16	-7.0	-0.88	0.16	-3.5	-0.77	0.12	-4.0	0.95
Mean Con Velocity (m.s^{-1})	1.78	0.15	2.2	1.67	0.16	1.6	1.55	0.09	1.2	0.98
Peak Ecc Velocity (m.s^{-1})	-1.40	0.23	-6.4	-1.37	0.28	-3.8	-1.18	0.19	-4.6	0.95
Peak Con Velocity (m.s^{-1})	3.23†	0.18	1.7	2.83*	0.17	1.1	2.57	0.15	0.9	0.99
Ecc Displacement (m)	-0.37*	0.10	-8.9	-0.34	0.04	-4.2	-0.27	0.06	-6.5	0.94
Con Displacement (m)	0.49	0.10	5.6	0.46	0.03	3.1	0.38	0.06	3.6	0.96
Area Under ECC F-v Curve (W.kg)	24.00	8.24	12.9	24.29	11.52	7.5	19.62	6.01	9.7	0.95
Area Under CON F-v Curve (W.kg)	75.45†	10.36	4.7	62.50	9.75	2.8	57.84	5.14	2.1	0.96

SD=Standard deviation; CV=Co-efficient of variation, ICC=intraclass correlation coefficient; RSImod=Reactive strength index modified; Ecc=Eccentric; Con=Concentric; RFD=Rate of force development; Fz=Force

† Significantly greater than all other groups

* Significantly greater than REC

Table 5-4 - Between Group Comparison of CMJ Variables.

Jump Variable	EJ vs RL		EJ vs REC		RL vs REC	
	ES	p	ES	p	ES	P
Jump Height (m)	2.4	<0.001	4.1	0.008	1.4	<0.001
RSImod	1.3	0.002	1.9	<0.001	0.7	0.454
Peak Ecc Fz (N)	0.1	0.948	0.2	0.945	0.0	1.000
Peak Con Fz (N)	0.5	0.470	0.1	0.475	0.0	1.000
Leg Stiffness (N.kg.m-1)	0.3	0.843	0.9	0.041	1.2	0.009
Eccentric Impulse (N.s)	0.1	0.945	1.0	0.087	0.8	0.150
Concentric Impulse (N.s)	2.4	<0.001	4.1	<0.001	1.4	0.004
Eccentric RFD (N.s-1)	0.2	0.825	0.5	0.453	0.2	0.801
Peak Eccentric Power (W)	0.1	0.975	0.8	0.340	0.6	0.230
Peak Concentric Power (W)	2.2	<0.001	3.5	<0.001	0.9	0.126
Eccentric Phase Time (s)	0.2	0.793	0.8	0.171	0.6	0.449
Concentric Phase Time (s)	0	0.99	0.8	0.07	1.0	0.083
Movement Time (s)	0	0.999	0.4	0.487	0.6	0.442
Mean Ecc Fz (N)	0.1	0.95	0	0.956	0.2	0.916
Mean Con Fz (N)	0.9	0.086	0.9	0.132	0.1	0.973
Mean Ecc Power (W)	0	0.998	0.7	0.363	0.6	0.315
Mean Con Power (W)	1.3	0.006	2.2	<0.001	0.6	0.354
Mean Ecc Velocity (m.s^{-1})	0.2	0.911	1	0.82	0.8	0.174
Mean Con Velocity (m.s^{-1})	0.7	0.764	1.9	0.35	0.9	0.754
Peak Ecc Velocity (m.s^{-1})	0.1	0.987	1	0.571	0.8	0.656
Peak Con Velocity (m.s^{-1})	2.3	<0.001	4	<0.001	1.6	0.002
Eccentric Displacement (m)	0.4	0.607	1.1	0.008	1.3	0.069
Concentric Displacment (m)	0.5	0.324	1.4	0.106	1.7	0.79
Area Under UNW-ECC F-v Curve (W)	0	0.997	0.6	0.474	0.5	0.413
Area Under CON F-v Curve (W)	1.3	0.003	2.2	<0.001	0.6	0.397

TPA results revealed differences in 95% CI control limits in force application between EJ and both other groups during both the unweighting and propulsion phases (EJ vs. REC differences at 2-15% and 90-99% movement time; EJ vs. RL differences at 2-6%, 90-99% movement time) despite no differences in the peak and mean values. Force-time curves are illustrated in Figure 5-2, Figure 5-3 and Figure 5-4, shaded areas denote non-overlapping 95% CI.
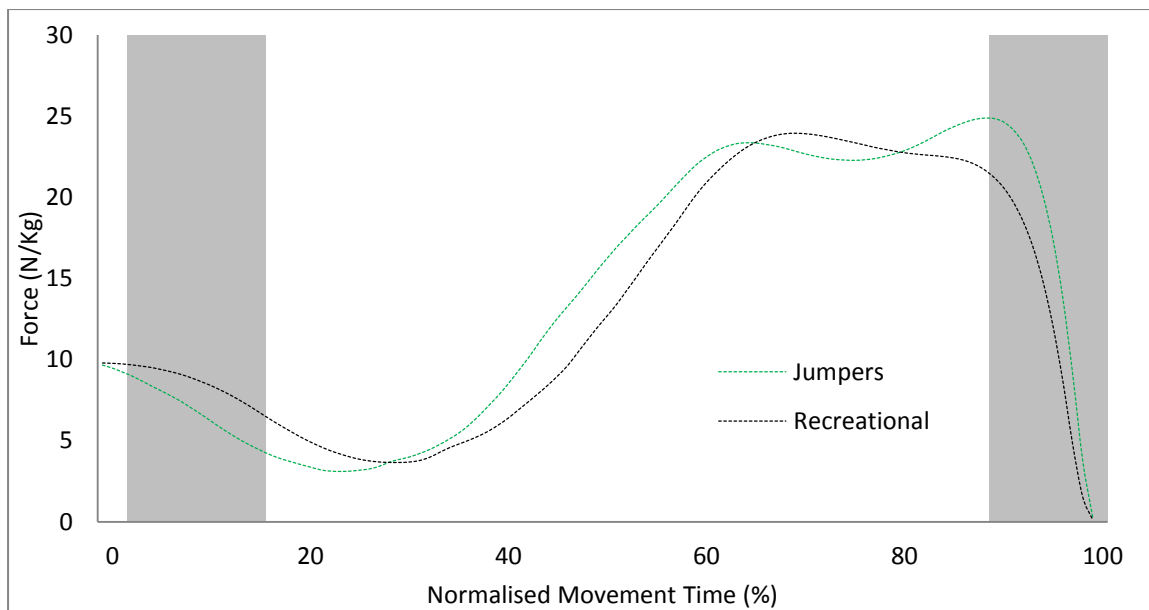
Figure 5-2 - Force-time curves of EJ vs. REC
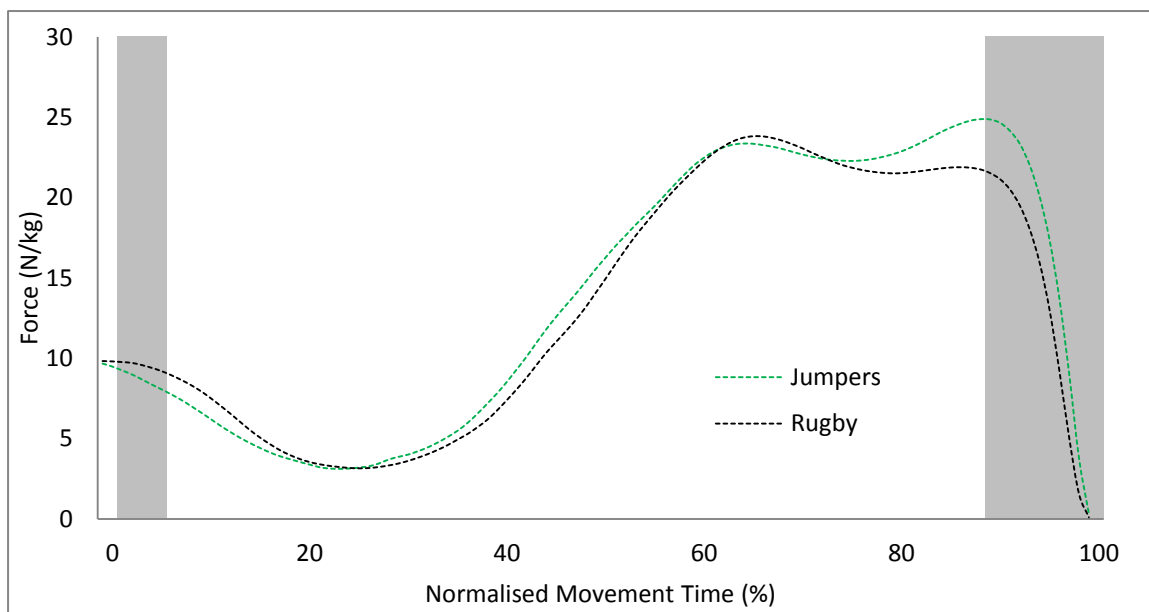
Figure 5-3 - Force-time curves of EJ vs. RL
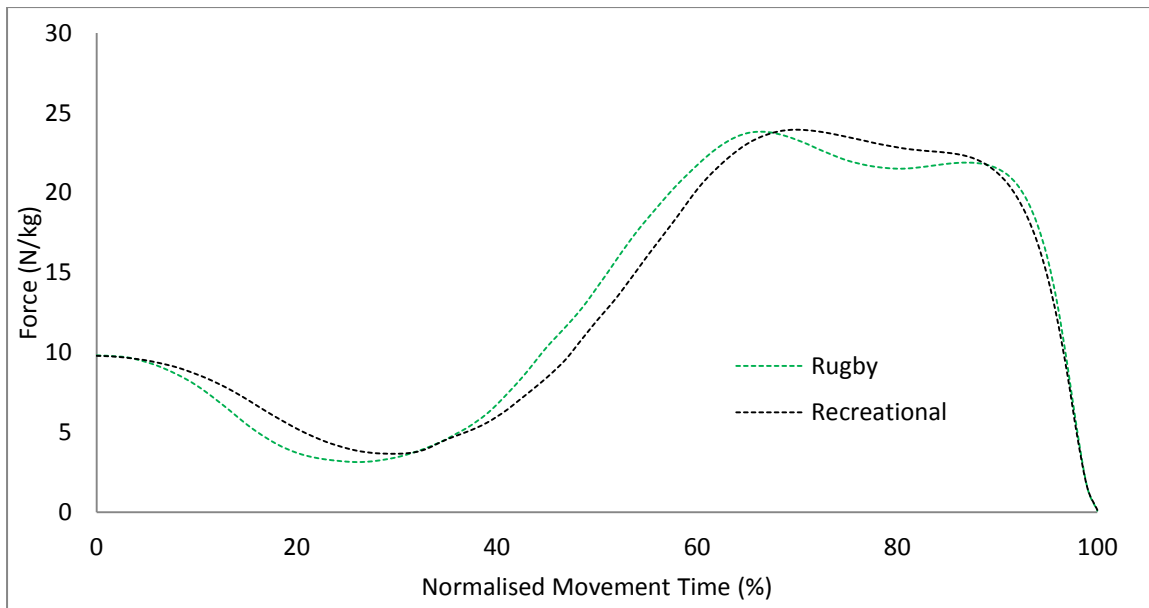
Figure 5-4 - Force-time curves of RL vs. REC

Analysis of the power-time curves showed greater negative power during the unweighting phase (9-16% and 40-47% movement time) in EJ in comparison with REC and during the propulsion phase in comparison with both other groups (87-100% movement time). Power-time curves are illustrated in Figure 5-5, Figure 5-6 and Figure 5-7.
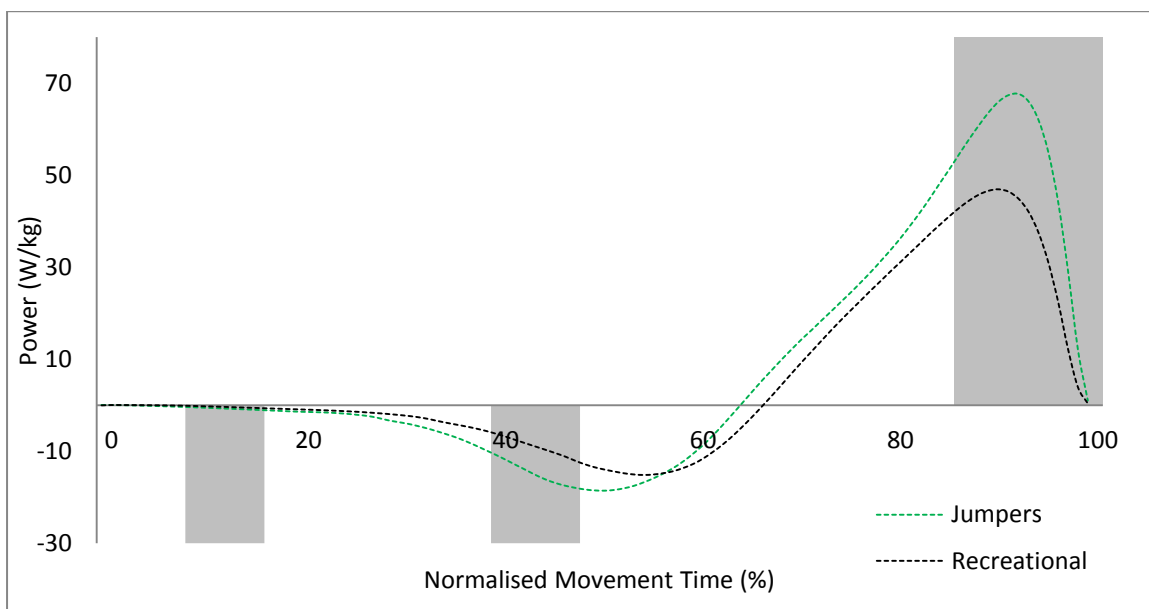
Figure 5-5 - Power-time curves of EJ vs. REC
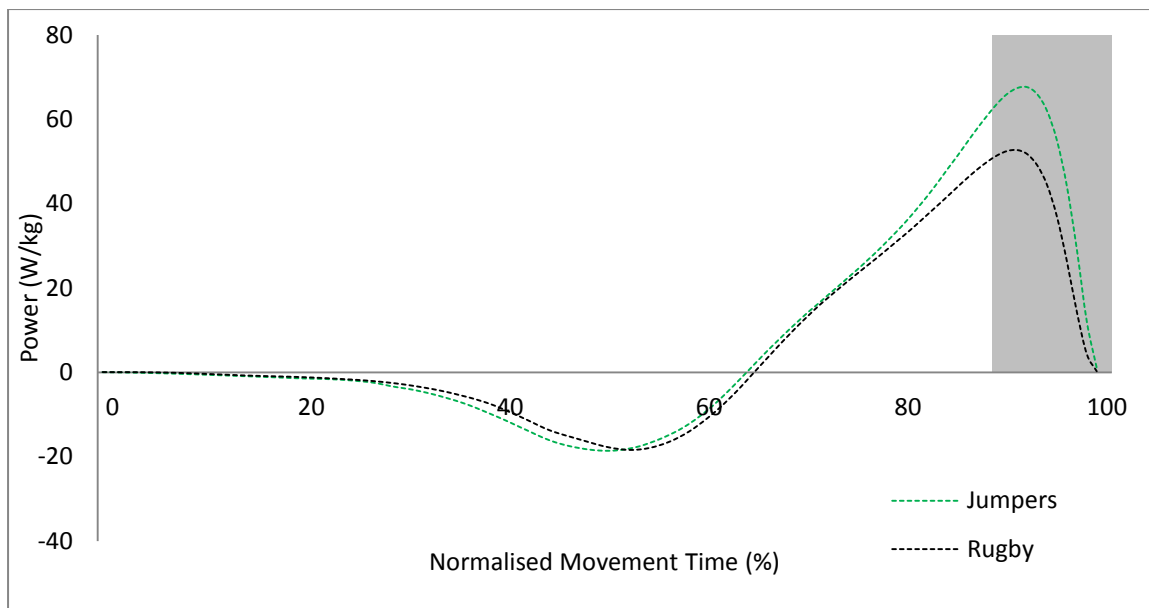
Figure 5-6 - Power-time curves of EJ vs. RL
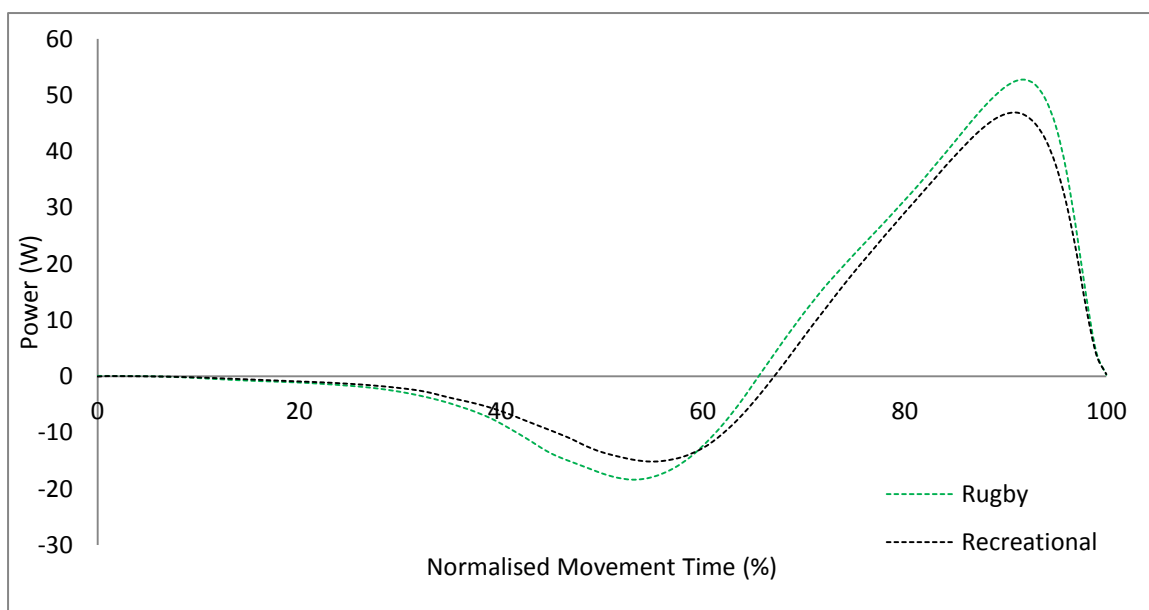
Figure 5-7 - Power-time curves of RL vs. REC

The pattern of a more rapid negative acceleration during unloading and a subsequent greater CoM velocity during propulsion being associated with superior jump performance was seen in all comparisons of velocity-time curves. Compared to REC, EJ showed greater negative velocity between 9-33% of movement time with greater positive velocity between 88-100% of movement time. A similar pattern was observed when comparing EJ with RL with differences seen between 9-11% and 94-100% of movement time. RL also differed from

REC between 16-17% and 92-100% of movement time. Velocity-time curve comparisons are illustrated in Figure 5-8, Figure 5-9 and Figure 5-10.
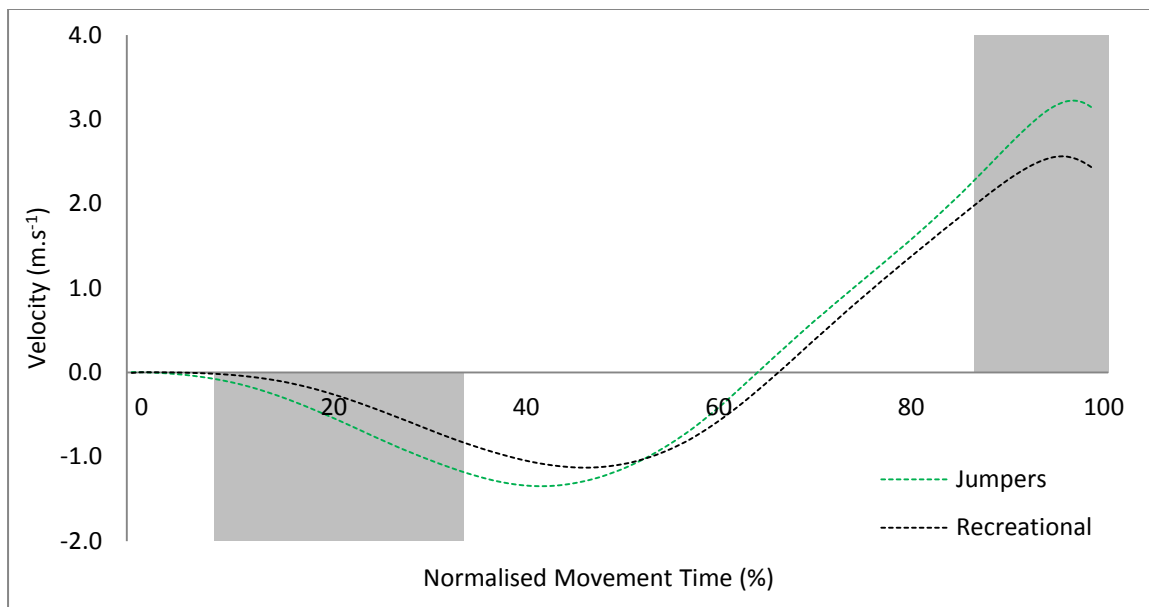
Figure 5-8 - Velocity-time curves of EJ vs. REC
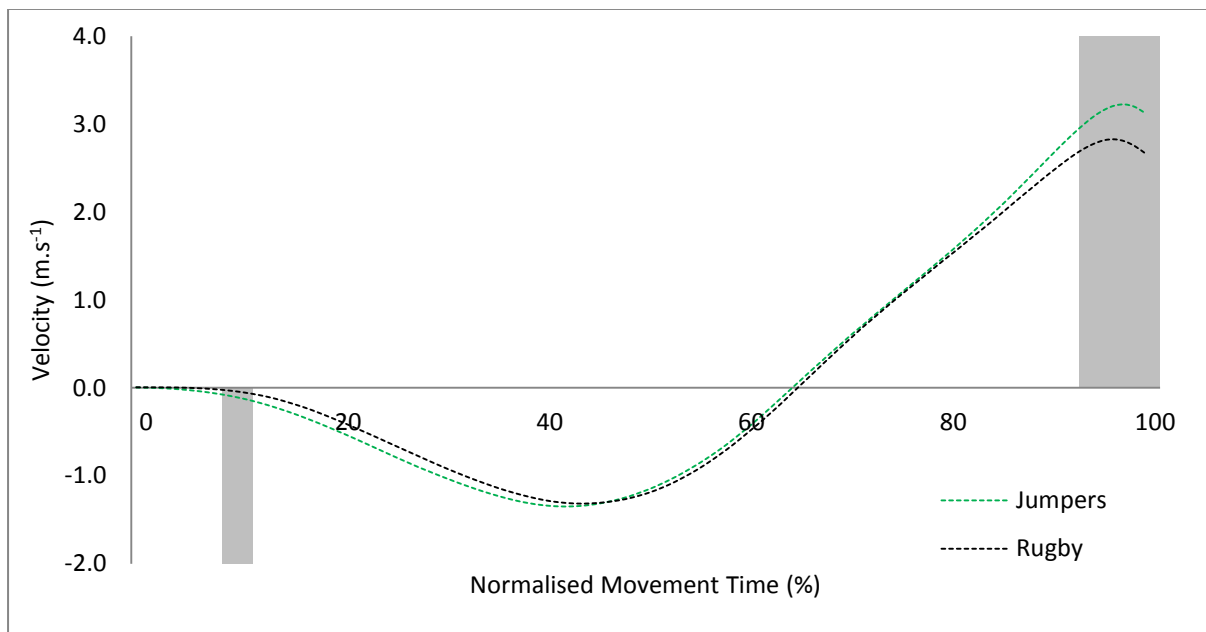
Figure 5-9 - Velocity-time curves of EJ vs. RL
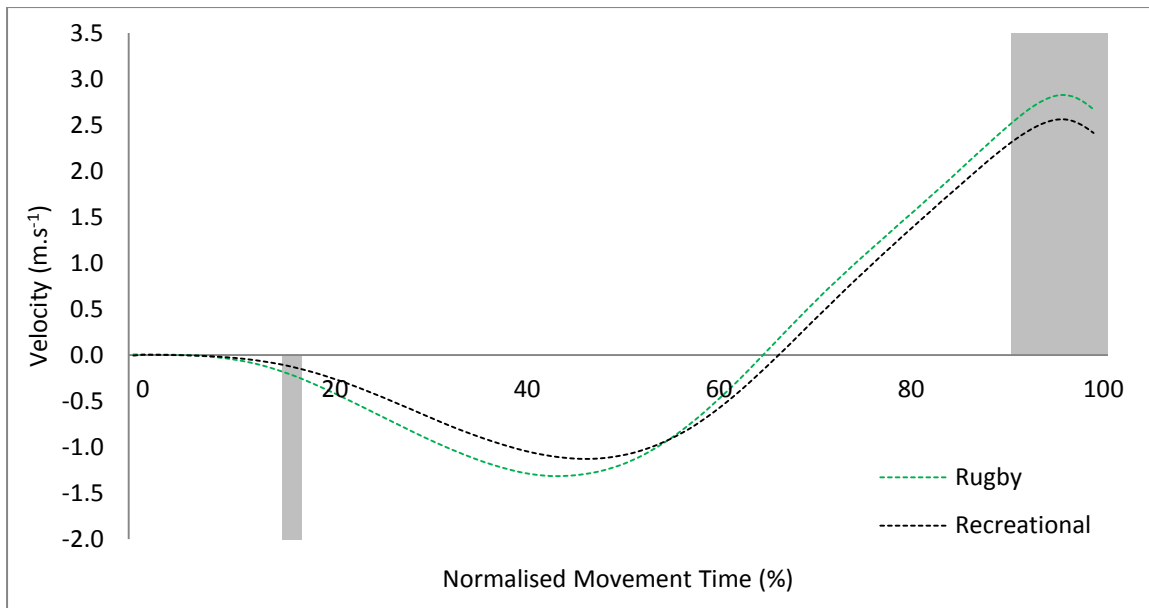
Figure 5-10 - Velocity-time curves of RL vs. REC

Comparison of displacement-time curves revealed large differences in eccentric and early concentric displacement between EJ and RL (18-67% movement time) and RL and REC (25-78% movement time) although no differences were seen between EJ and RL. Displacement-time curves are illustrated in Figure 5-11, Figure 5-12 and Figure 5-13.
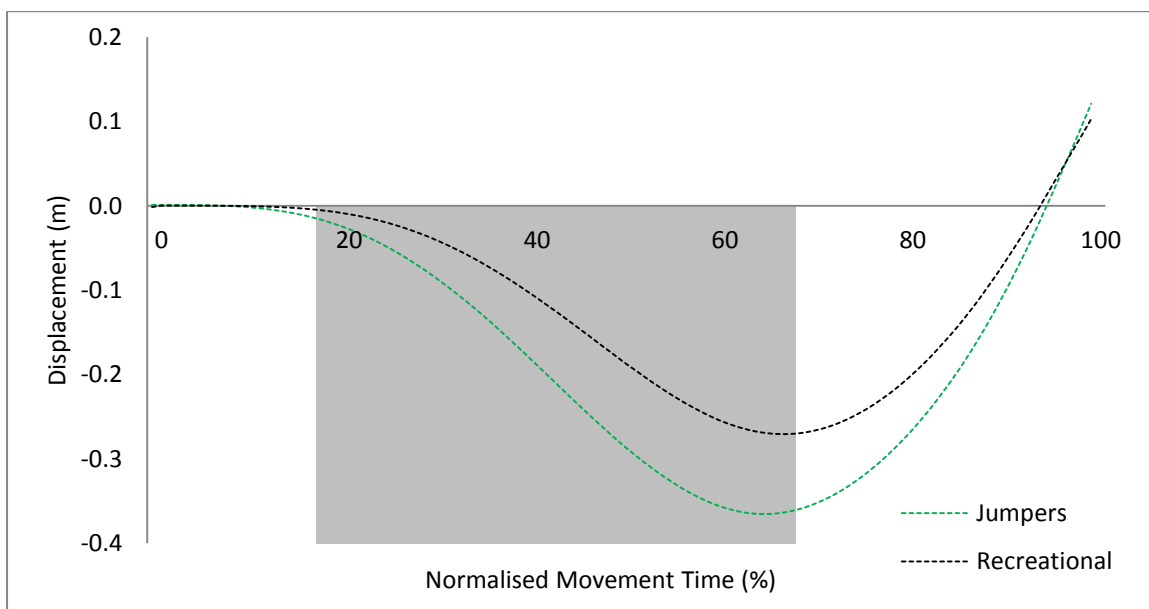
Figure 5-11 - Displacement-time curves of EJ vs. REC
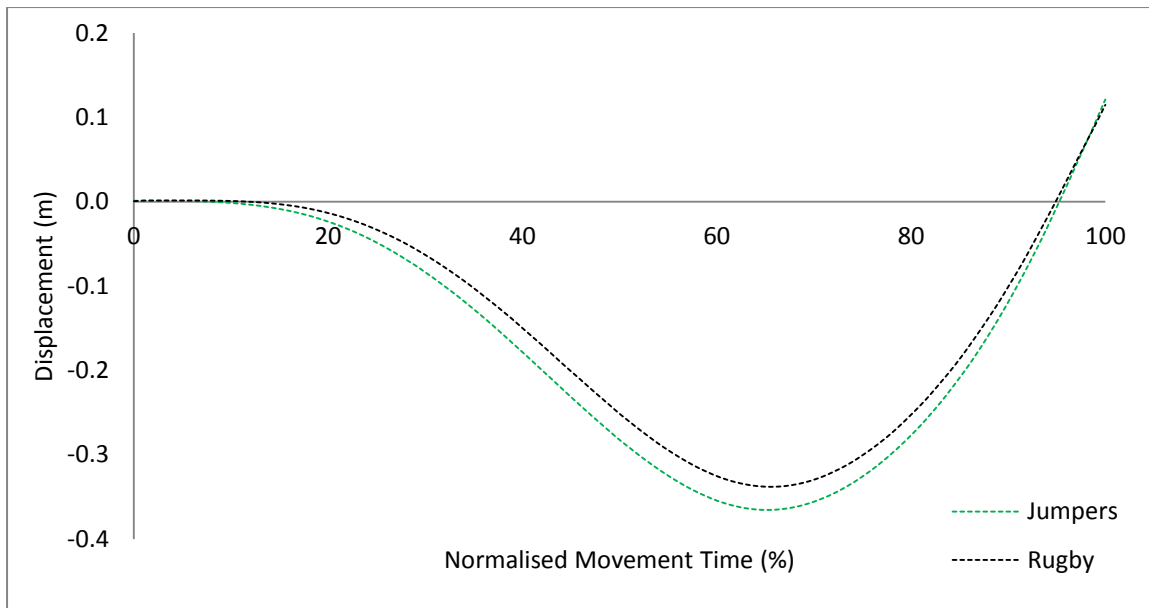
Figure 5-12 - Displacement-time curves of EJ vs. RL
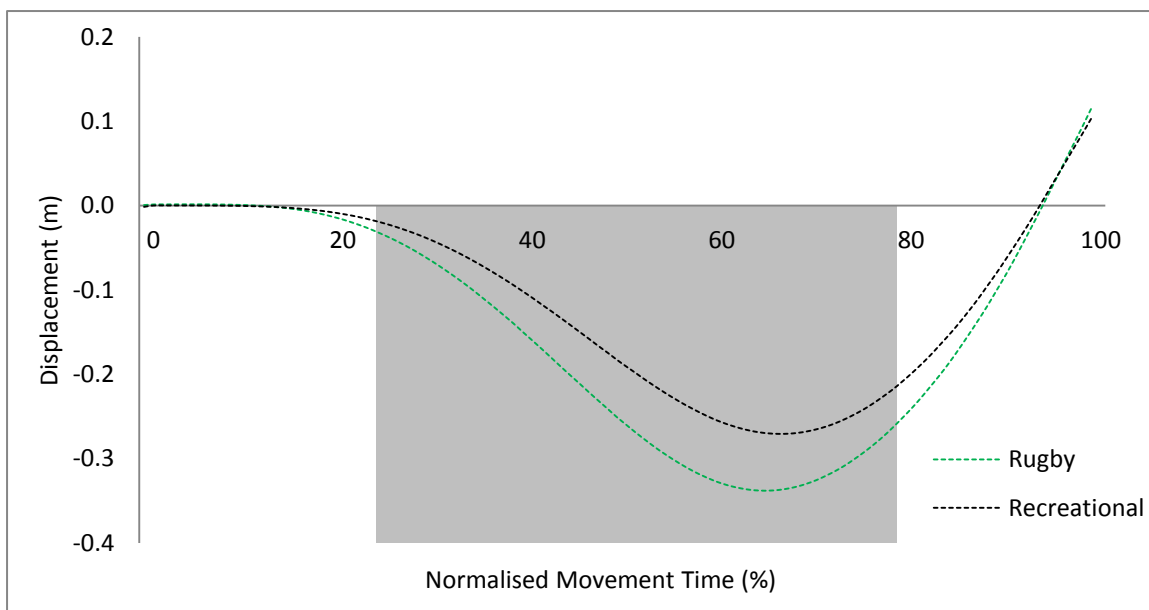
Figure 5-13 - Displacement-time curves of RL vs. REC

Force-velocity curve comparisons are illustrated in Figure 5-14, Figure 5-15 and Figure 5-16. The association between CMJ performance and force-velocity during unweighting and propulsion is notable, as is the similarity in force at zero velocity during all comparisons.
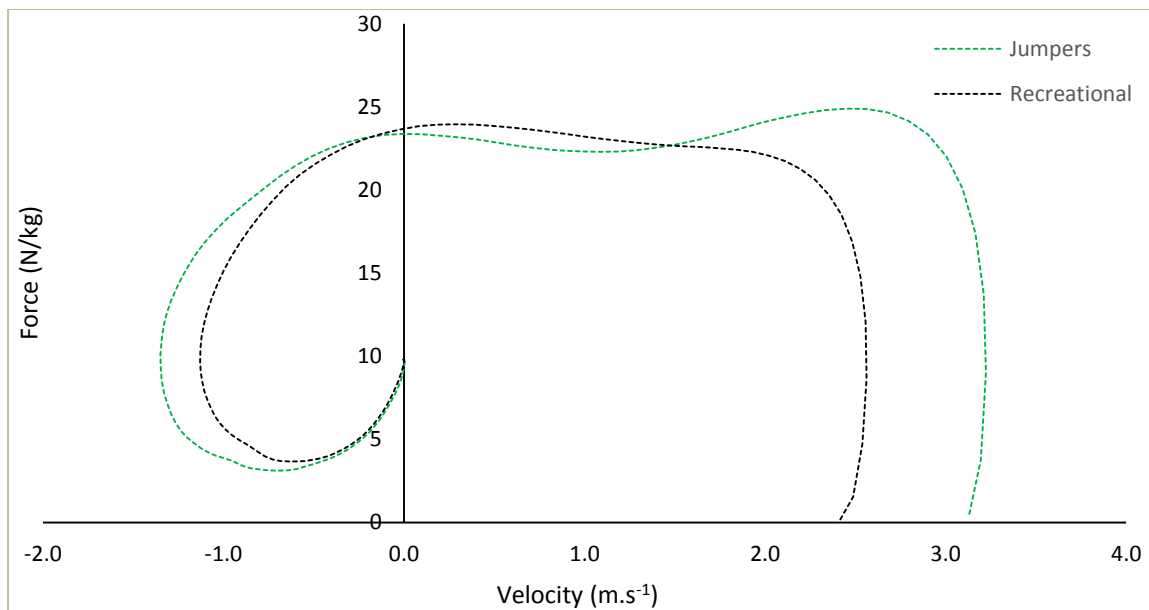
Figure 5-14 - Force-velocity curves of EJ vs. REC
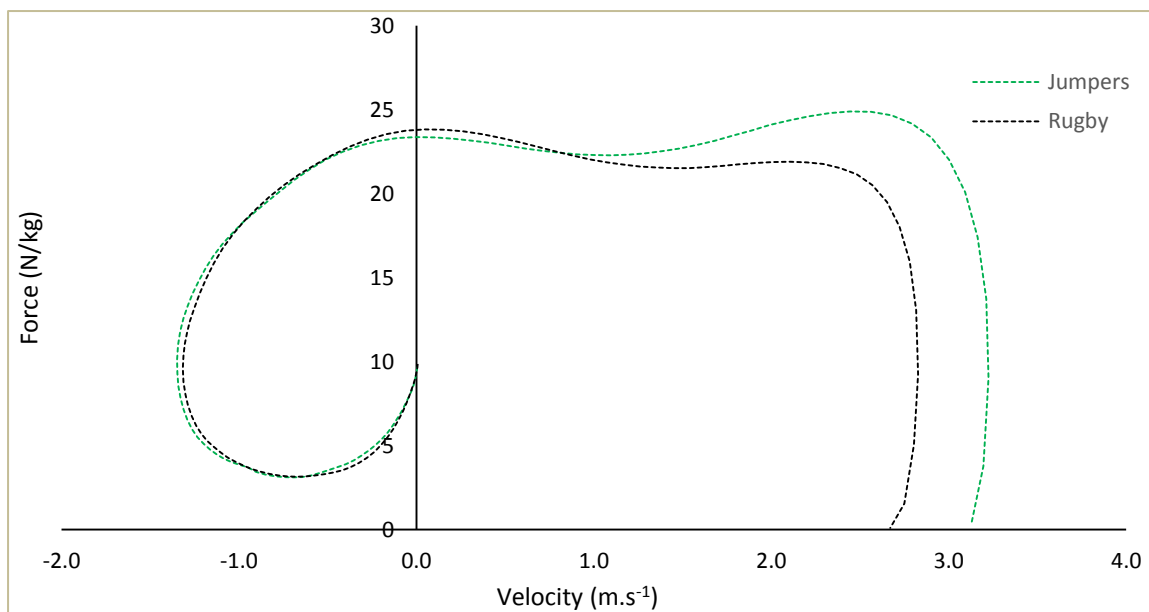
Figure 5-15 - Force-velocity curves of EJ vs. RL
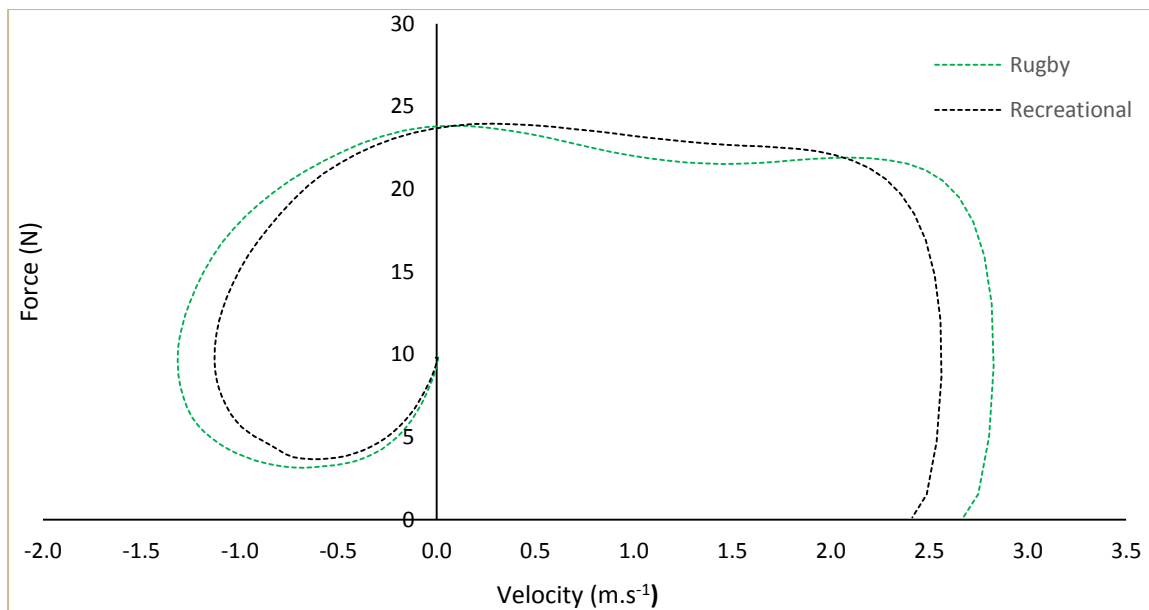
Figure 5-16 - Force-velocity curves of RL vs. REC

5.6 Discussion

To the author's knowledge, this was the first study to conduct a three-way cross-sectional comparison of heterogeneous athletic populations in order to gain a greater understanding of the kinetic, kinematic and temporal characteristics which underpin CMJ performance. The results confirmed the hypothesis that EJ athletes would achieve superior jump height over RL who in-turn would out-perform REC. Two distinct jump strategies emerge from the results which showed that both EJ and RL utilised a movement pattern characterised by greater depth of CoM descent during unloading. Increased depth of CoM displacement resulted in a moderately greater eccentric impulse compared to the REC group. This appears to be primarily as a result of a moderate but non-significant increase in eccentric phase duration in EJ and RL which, when performed with similar mean force, provides a greater impulse. The greater depth of descent by EJ and RL also led to a longer concentric phase during which a greater concentric impulse was generated leading to greater peak velocity. EJ achieved superior jump performance over RL despite utilising a similar strategy. The differentiating factor between these two groups would appear to be the capacity of EJ to produce concentric impulse which it is hypothesised is a result of neuromuscular capabilities rather than jump strategy.

Previous studies have compared high and low performing jumpers (Cormie et al., 2009, McMahon et al., 2017b, Sole et al., 2017), male and female athletes (McMahon et al., 2017a, Rice et al., 2017) and also senior versus academy rugby league players (McMahon et al., 2016). The findings of significant differences in performance across the three groups, presents an opportunity to explore the mechanisms which underpin these differences. It should be noted that there were no significant differences in movement time and therefore differences in RSI-mod are driven by superior jump height. It is unclear whether the superior performance is the result of genetic ability or a consequence of training (or a combination of the two). This may be an important distinction as Cormie et al. (2009) found the mechanisms underpinning superior performance to differ between cross-sectional comparisons of high and low jumpers and a longitudinal comparison following a training protocol. These alternative mechanisms will be discussed further below but may be summarised by superior neuromuscular capacity seemingly being expressed through augmented performance during the concentric phase whereas training adaptations appear to be driven through a more effective use of the eccentric phase.

The rapid expression of force during the concentric phase also appears to be a primary factor in superior performance with significant and large effect in peak concentric power distinguishing EJ from both other groups (ES=2.2-3.5, p<0.001). A moderate trend was also seen between RL and REC (ES=0.9, p=0.126), although this was not statistically significant. This phenomenon is illustrated through TPA during which EJ achieved significantly greater power during 87-100% of movement time in comparison with other groups. These findings are consistent with other studies that have found superior jump height to be associated with increased peak concentric power and through TPA around the final 10% of the movement time (Cormie et al., 2009, McMahon et al., 2017b, McMahon et al., 2016, Sole et al., 2017).

No significant differences were observed between peak or mean eccentric or concentric force across any of the groups. However it should be noted that TPA revealed that EJ achieved significantly greater concentric force (90-100%) in comparison with both other groups. Similar findings were observed by Cormie et al. (2009) and McMahon et al. (2016) who found no differences in peak eccentric or concentric force but greater force production during the end of the concentric phase (95-98% and 87-100% respectively), although it

should be noted that the latter was absolute force only. This highlights the potential of TPA to provide a more sensitive level of insight beyond peak and mean values. When combined with the differences in impulse this provides valuable insight into the pattern of force application. Given that impulse is the product of force over time, the finding of no differences in mean and PF suggests that greater impulse has been achieved through a more sustained application of force over a longer period. This is in contrast to the findings of McMahon et al. (2017b). However this study distinguished jumpers by RSI-mod score. As a reduced movement time leads to a greater RSI-mod score the high performing group may be naturally skewed to those who utilise a shorter movement time. Whilst a direct link to performance is not clear, visual inspection of the force-time signatures shows a more pronounced bimodal application of eccentric-concentric peaks in EJ and RL than REC. Such a pattern was found to be a key adaptation in response to power training by Cormie et al. (2009). Therefore this may reflect the training background of these two groups rather than genetic physiological advantage. By a similar token, the force-velocity curves illustrated in Figures 6a-6c provide a useful insight into the more rapid unloading and concentric force application associated with greater performance. The force-velocity curve comparison of EJ versus RL (Figure 6b) also demonstrates a pattern which is almost identical throughout the first $^2/_3$ of the movement but is clearly distinguished by superior performance by jumpers during the final $^1/_3$. This may suggest that the jumpers utilised a similar strategy of force application but possessed a physiological advantage, including a smaller body mass but similar height. Clearly the strength and power characteristics of EJ are highly suited to the CMJ (McBride et al., 1999) and such an advantage is therefore unsurprising.

A number of the kinetic differences seen between the groups may be better understood through an evaluation of kinematic differences. Significantly greater negative displacement with large effect size differences were seen in EJ than REC with a large trend towards significant (ES=1.3, p=0.069) between RL and REC. However these findings need to be considered in the context of EJ and RL being significantly taller than REC and therefore the greater negative displacement cannot automatically be assumed to represent a great range of movement though joint angles. Despite this caution, the REC group had significantly greater leg stiffness in comparison with both other groups. Combined, these findings suggest a deeper, more compliant CMJ technique being deployed by EJ and RL in

comparison with a shallow and stiffer technique in REC. These finding replicate those of Cormie et al. (2009) and McMahon et al. (2016), both of which observed greater negative displacement being associated with enhanced performance. This raises an interesting question as to the reason why less effective jumpers fail to utilise this apparently superior technique. The depth of descent in a CMJ is typically well within the available range of motion of the squat pattern. Therefore it is highly unlikely that differences are the result of limited structural range of movement. Instead it may be hypothesised that advanced jumpers possess greater strength levels which instinctively enable a greater depth of descent. Furthermore the better trained athletic groups may possess superior coordination of these well trained movements thus enabling greater range of movement within a similar time frame. Strength levels of subjects were not measured during the present study but this hypothesis is supported by the findings of Cormie et al. (2009) who observed greater strength levels in jumpers versus non-jumpers during 1-repetition maximum squatting (squat 1RM:BW ratio - jumpers = 1.93±0.22; non-jumpers=1.40±0.27; p<0.001).

Total movement times were similar across all three groups with no significant differences observed. The same pattern was also seen in eccentric phase time, although a non-significant trend towards a longer eccentric phase was seen in EJ versus REC athletes (ES=0.8, p=0.17). However, whilst differences were just short of statistical significance, large effect size differences were observed between both EJ (ES=0.8, p=0.07) and RL (ES=0.8, p=0.08) in comparison with REC. These findings are consistent with an emerging picture of enhanced performance being achieved through an increased opportunity to accumulate impulse and generate concentric power following a greater depth of descent and subsequent concentric phase movement time.

Comparisons of peak and mean eccentric velocities revealed no significant differences. However large effect size differences were observed in peak concentric velocity across all groups (ES=1.6-4.0, p<0.005) with superior jump performance being associated with greater peak concentric velocity. No significant differences were observed in mean concentric velocity, which may indicate that the greater peak concentric velocity was achieved through an extended concentric phase and therefore a larger window of time to develop CoM velocity.

The model of CMJ technique illustrated through kinetic and kinematic analysis in the present study builds upon the emerging picture from recent research (Cormie et al., 2009, McMahon et al., 2017a, McMahon et al., 2017b, McMahon et al., 2016, Rice et al., 2017, Sole et al., 2017). Such a model sees the concentric phase of the jump being the critical element which differentiates between levels of jump performance. Within such a model the most notable element of the eccentric phase is a greater depth of negative displacement which appears to enable an extended concentric phase. Such a model can be viewed in contrast to that described by Cormie et al. (2009) and Cormie et al. (2010b). These studies present an adaptation to training which sees enhanced CMJ performance following an augmentation of the eccentric phase and a stiffer technique. Further research is required to confirm that two such distinct mechanisms can be attributed to training versus genetic physiological potential. However based upon current evidence it would appear that genetic potential is most commonly expressed within the concentric phase of movement whereas training directs the athlete towards a more effective expression of their strength qualities during the eccentric phase.

5.6.1 Practical Applications

The present study provides further evidence of the capacity to augment jump performance through the adoption of a technique characterised by augmented impulse during the eccentric phase via a greater negative CoM displacement. This involves a rapid unweighting and a greater depth of displacement thus extending the duration of the eccentric phase. Providing an athlete possesses the neuromuscular qualities to achieve such a technique without negatively impacting the subsequent concentric phase this is recommended as an optimal model of CMJ performance. Therefore coaches are encouraged to work towards such a model, primarily through the development of neuromuscular qualities to support it rather than through the specific coaching of CMJ technique in such a manner. This is in harmony with the work of Cormie et al. (Cormie et al., 2009, Cormie et al., 2010b, Cormie et al., 2011, Cormie et al., 2010a) who suggest that an effective strategy for developing jump performance may be to first develop underpinning strength qualities before then using jump training to enable athletes to adapt jump strategies to best make most effective use of force.

Finally, insights into the proximity of an athlete's CMJ kinetic profile to the optimum model may also provide an indication of likely capacity for performance improvements. For example, the absence of a highly augmented eccentric phase, which appears to reflect a training effect, may infer that an individual has greater performance capacity by applying existing strength qualities in such a manner.

5.6.2 Limitations

The number of subjects within each group is somewhat limited, reflecting the challenge of collecting data within elite athlete populations. As a result, a number of variables demonstrate large effect sizes which are not significantly different. These results are practically meaningful but would benefit from further research using larger subject numbers.

The absence of an assessment of the physical strength of subjects may be considered a limitation within the present study. Such an evaluation would enable a more enlightened consideration of the factors likely to have underpinned differences in jump performance. Similarly an evaluation of the training history of subjects may help to inform conclusions regarding the likelihood of superior performance being the result of training adaptations or physical talent. Inclusion of these additional assessments may prove beneficial in future research.

5.6.3 Summary

The findings of the present study provide a unique and novel comparison of jump characteristics across two distinct elite athlete populations and a comparison with non-elite counterparts. A model of CMJ performance emerges which describes a continuum of performance variables underpinning effective jump technique differentiating progressively across athletic populations. The jumping model would appear to be characterised by a greater eccentric CoM displacement with a relatively compliant technique. The concentric phase is then longer allowing for a greater accumulation of concentric impulse and subsequently greater concentric peak power and velocity. Coaches are encouraged to

develop strength qualities to support the ability to rapidly unweight without negatively affecting a subsequent concentric phase. These qualities should be developed alongside rehearsal of the specific movement skill of a rapid unloading-loading coupling.

Having demonstrated the utility of TPA to provide valuable insight into the kinetic and kinematic characteristics of ballistic exercise the following chapter will apply the methodology to a plyometric task.

Chapter 6 - A Comparison of Drop Jump Temporal Phase Characteristics in Elite Athletes

6.1 Overview

Previous work within this thesis and the wider literature has been based on an approach of assessing peak and mean values of various kinetic variables to describe and understand plyometric performance. In Chapter 5, a novel approach known as temporal phase analysis, was applied to the assessment of kinetic data during ballistic jumping. Such an approach explores the pattern of force application and provides a more detailed level of analysis than simply peak and mean values alone. This chapter will explore the potential for such a methodology to enhance the assessment of plyometric jumping. By evaluating the performance of a group of elite jumpers it is also the intention to gain further understanding of the kinetic and kinematic characteristics which underpin effective plyometric performance.

6.2 Abstract

The purpose of this study was to apply TPA to the drop jump in order to explore the factors which underpin effective performance. The TPA methodology has previously been applied to evaluate kinetic and kinematic characteristics of effective CMJ performance but has not been applied to a plyometric exercise. Ten elite male track and field athletes performed 50 repetitions of a 40 cm drop jump (10 sets of 5) with ground reaction forces collected throughout. Jumps were ranked according to RSI score with the 50 best (BEST) and 50 worst (WORST) scores compared as groups. BEST achieved superior RSI scores (BEST=3.08±0.11, WORST=1.49±0.11) through a technique characterised by a short eccentric phase (BEST=60±6 ms, WORST=140±21 ms, ES=5.2, p<0.001) with high mechanical stiffness (BEST=10.7±1.9 N.kg.m^{-1}, WORST=4.31±1.2 N.kg.m^{-1}, ES=4.0, p<0.001) leading to greater force at zero velocity than WORST (BEST=55.1±12.2 N.kg, WORST=31.6±4.9 N.kg, ES=2.5, p<0.001). This was followed by a concentric phase which, although shorter in duration than WORST, achieved greater concentric impulse (BEST=3.34±0.17 N.kg.s, WORST=2.93±0.22

N.kg.s, ES=2.1, p<0.001), concentric PF (BEST=63±8.9 N/kg, WORST=36±3.6 N/kg, ES=4.0, p<0.001) and concentric peak power (BEST=115±4.3 W/kg, WORST=75±5.2 W/kg, ES=8.4, p<0.001). The TPA highlighted a movement pattern which was characterised by a more rapid unweighting but smaller negative displacement of CoM in BEST and a quicker return to zero velocity followed by a large expression of concentric power within the concentric phase. These results provide further insight into the characteristics of effective drop jumping which are represented by a brief ground contact time and stiff landing technique leading to an augmented concentric phase. Furthermore, the present study demonstrates for the first time, the efficacy of the TPA to provide additional insight into plyometric exercise.

6.3 Introduction

The application of TPA to explore the kinetic characteristics of the CMJ within the literature has been reviewed within section 2.4. The methodology has demonstrated efficacy in distinguishing between jump characteristics under different loading conditions (Cormie et al., 2008), pre- and post- training (Cormie et al., 2009, Cormie et al., 2010b), between sexes (McMahon et al., 2017a, Rice et al., 2017), athletic populations (McMahon et al., 2016) and jumping abilities (McMahon et al., 2017b, Sole et al., 2017). In addition to establishing TPA as an effective methodology for interrogating the kinetic patterns of a CMJ, these studies have provided insight into characteristic patterns which may differ according to the background of the subject group.

It would appear that those with greater neuromuscular abilities achieve superior jump heights than their weaker counterparts chiefly through a larger expression of impulse through the concentric phase of a jump (Cormie et al., 2008). However, it would also appear that training regimes which elicit gains in CMJ jump height are often the result of an adapted kinetic pattern which is characterised by an augmented eccentric phase which serves as a "primer" for greater performance during the concentric phase (Cormie et al., 2009, Cormie et al., 2010b). This may typically involve a more rapid unweighting, possibly with a greater depth of descent, followed by greater braking forces and eccentric impulse. It

has been hypothesised that such a strategy enables greater loading of the SSC to achieve augmented jump performance.

Chapter 5 added to this body of work by comparing CMJ TPA findings across 3 populations (EJ, RL and REC). These results found that EJ and RL achieved superior performance over REC counterparts whilst demonstrating an alternative movement strategy in-keeping with the model described above. The EJ group achieved superior heights over RL despite using a similar strategy but achieved greater force outputs during the concentric phase as has been proposed as representing greater neuromuscular ability.

Whilst the use of TPA to evaluate CMJ has become established within the literature, somewhat surprisingly, no studies to date have utilised the technique in the context of a plyometric task (i.e. one involving a rebound). The drop jump is the most commonly evaluated plyometric exercise within the literature (see section 2.2.2). This represents a compelling choice as the exercise is conducted under well controlled conditions. There is minimal prior movement involved other than stepping in a controlled manner from a box. The drop height is known and can be easily manipulated and the movement is performed almost exclusively in the vertical plane thus making analysis relatively simple.

A TPA analysis of a plyometric exercise raises a number of potential questions. The rebound element of a plyometric movement inherently places greater emphasis on the eccentric phase with greater SSC contribution in comparison with a ballistic equivalent (e.g. CMJ vs. drop jump) (Bobbert et al., 1996a). Given the apparent significance of changes to the eccentric phase seen in CMJ analysis, the significance of this when evaluating effective plyometric performance needs to be understood. The TPA has been used as a means of exploring how the most effective jumpers achieve greater heights with a view to developing an optimal model. Therefore there would appear to be merit in studying the same question with regard to plyometric jumping. It could be hypothesised that the significance of the SSC in plyometrics may lead to this being a greater differentiating factor than has already been seen in performances of CMJ. Alternatively the potential of the SSC may be maximised through the loading achieved during rebound and thus concentric force may differentiate between the best performers.

The purpose of the present study is to provide a novel application of TPA in comparing kinetic characteristics within elite athletes during a plyometric exercise. Specifically, this enquiry will compare drop jump performances between the most and least effective jumps. The reactive strength index provides a useful metric for assessing plyometric jump strategies as both jump height and ground contact duration are considered. The most and least effective jumps will be compared in an attempt to distinguish the mechanical characteristics of effective jumping. This will represent an extension of the existing literature from a CMJ (ballistic) to a drop jump (plyometric). Furthermore the results may offer new insight into the "kinetic signature" of an elite jumper. It is hypothesised that the most effective jump performances will be achieved through force application strategies which utilise a stiffer landing and reduced centre of mass (CoM) displacement and consequently generate greater impulse through higher PF accumulated over shorter ground contact durations.

6.4 Methods

6.4.1 Subjects

Ten adult male track and field athletes (age=23.2 ± 3.6 years; mass=78.8 ± 5.0 kg; height=1.87±0.04 m), competitive at national and international level, volunteered for the study. Based on the criteria which define an elite athlete as described by (Swann et al., 2015) ,these subjects would be considered in the highest category in at least 80% of the defined criteria. The group regularly performed plyometric exercises twice weekly within their normal training programmes. All subjects provided informed consent before participation and ethical approval for the study was obtained through the Institutional Review board.

6.4.2 Testing

Immediately prior to testing all subjects completed their own personal warm-up, followed by a prescribed plyometric preparation warm-up which was written and coached by a United Kingdom Strength & Conditioning Association Accredited Coach.

Testing consisted of 10 sets of 5 repetitions of a 40 cm drop jump, reflective of a typical plyometric training session for these athletes and consistent with training guidelines (Potach and Chu, 2000, Ebben, 2007). Subjects were instructed to attempt maximal jump height whilst keeping ground contact time minimal (Young et al., 1999). Each repetition within a set was performed in a consecutive manner with a pause to remount the box and regain composure. Each set was separated by 3 minutes of rest. A 60x90 cm force platform (Model 9287BA Kistler, Winterthur, Switzerland) mounted within the floor of an athletics venue, sampling at a frequency of 2000 or 3000 Hz, was used to measure ground reaction forces of all repetitions (3000 Hz was originally selected to enable synchronisation with 300 Hz filming but was reduced to 2000 Hz when the use of filming was removed from the methodology). This frequency was used to ensure at least 500 samples were available for a given athlete's ground contact time. The typical ground contact time for a drop jump is approximately 250 ms requiring a sampling frequency of at least 2000 Hz or greater for shorter contact jumps in order to enable 500 unique data points to be taken for TPA. For this reason a significantly higher sampling frequency was required in comparison with previous CMJ study methodologies (Cormie et al., 2008, Gathercole et al., 2015a).

6.4.3 Analysis

The raw vertical force-time data for each jump trial were exported as text files and analysed using a customised Microsoft Excel spreadsheet (version 2016, Microsoft Corp., Redmond, WA, USA). Force-time data was used to calculate kinetic variables, the methods for which are described in Table 6-1.

Table 6-1 - Calculation of performance variables derived from force-time data.

Variable	Calculation Method
Velocity	Vertical force (minus BW) divided by body mass and integrated using trapezoid rule
Power	CoM velocity multiplied by vertical force at each time point
Displacement	Double integration of vertical force data

The instant of touchdown for each drop jump was considered to have occurred at the first point at which vertical force exceeded 20 N. This threshold was selected based on the

author's experience that such as threshold minimises the risk that residual noise within the system is not incorrectly interpreted as ground contact by the subject. Jump phase identification was performed using the same methods described by (McMahon et al., 2016) with the only adjustment being the absence of an unweighting phase during the drop jump. Velocity of impact was predicted from drop height (see section 4.4.4). The eccentric phase of the jump was defined as occurring between the instants of touchdown and zero CoM velocity. The concentric phase of the jump was deemed to have occurred between the instant that CoM velocity exceeded $0.01m.s^{-1}$ and the instant of take-off as defined as vertical force falling below 20 N. These phases are illustrated in Figure 6-1.
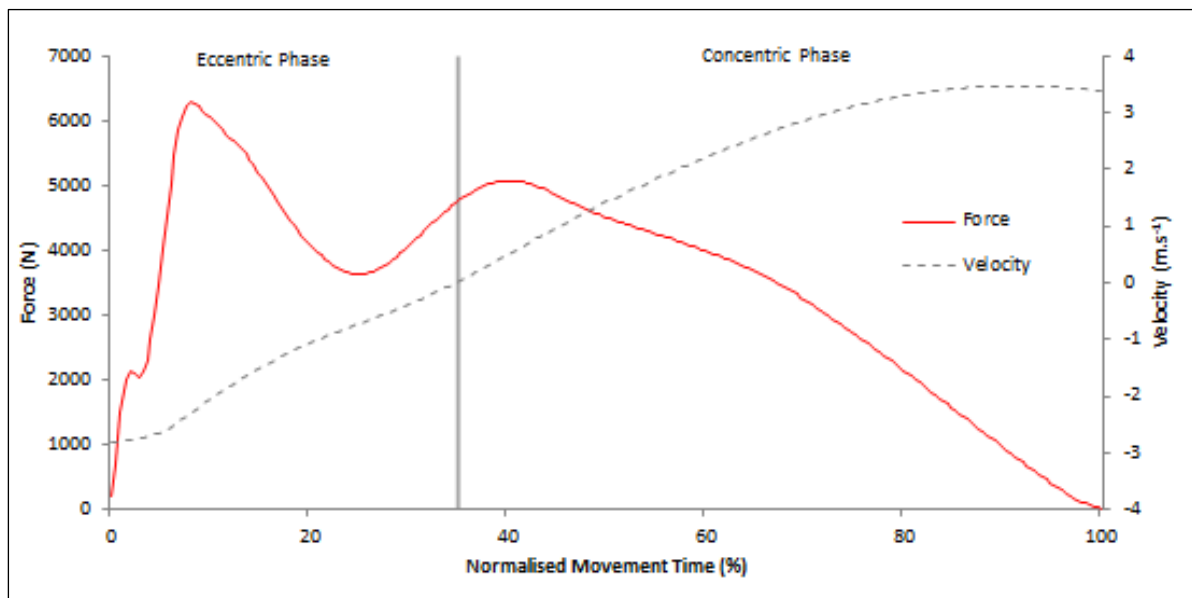
Figure 6-1 - Jump phase identification based on mean data for BEST group

Eccentric and concentric PF and peak power were defined as the maximum vertical force and power values, respectively, attained during the eccentric and concentric phases of the jump.

Impulse was calculated during both the eccentric and concentric phases of the jump as the area under the net force-time curve (minus BW) using the trapezoid rule. Area under the force-velocity curve was calculated from the instant of touchdown to the instant of take-off using Simpson's rule (Cormie et al., 2008). Mean eccentric RFD was calculated as eccentric PF divided by the time taken to reach this peak value from the onset of the eccentric phase.

All kinetic data were also divided by body mass to normalise comparison of these data between groups. Jump height was derived from vertical velocity at take-off (Moir, 2008). Reactive strength index (RSI) was calculated as jump height divided by contact time (Peng et al., 2011). Stiffness was calculated as the change in force divided by the associated eccentric phase displacement.

The TPA was conducted using the methodology described within the previous chapter. The time delta between samples of the force-, power-, velocity-, and displacement-time curves was modified and resampled so that each curve, from initial ground contact to toe-off, equalled 500 samples. This resulted in an average sample frequency of 1013±238 Hz. A total of 500 drop jumps were analysed and were ranked by RSI scores. The 50 best scoring jumps (BEST) were compared with the 50 worst scoring jumps (WORST). This resulted in both groups being made up of jumps from a number of different subjects. The identity of the subjects of which each group was comprised was not considered to be methodologically important as the aim of the study was to contrast levels of performance rather than individual subjects per se. Differences in force-, velocity-, power-, and displacement-time curves were determined by plotting the time-normalized average curves for each group along with the corresponding upper and lower 95% confidence intervals (CI) to create upper and lower control limits and identifying non-overlapping areas with the movement considered over 100 intervals (0-100% of movement time).

The statistical analyses were undertaken with SPSS V23.0 for Windows (SPSS, Inc., Chicago, IL). Descriptive statistics (mean ± SEM) were computed for all performance variables. Shapiro-Wilks testing revealed that data did not meet parametric assumptions therefore means were compared using the Mann-Whitney test. The level of significance was set at $p \leq 0.05$ for all analyses. A two-way random-effects model intraclass correlation coefficient (ICC) was used to determine the relative between-trial reliability of each variable. ICC values ≥ 0.80 were interpreted as being highly reliable (Cortina, 1993). Cohen's d effect size (ES) statistics were used to evaluate the magnitude of the difference between groups according to criterion of > 0.8 large, 0.5–0.8 medium, 0.2–0.5 small (Cohen, 1988).

6.5 Results

All variables demonstrated high reliability (ICC=0.87-0.99) with the exception of leg stiffness (ICC=0.63) and peak eccentric power (ICC=0.54). RSI scores for the BEST and WORST jumps enabled distinction between these two groups with large significant differences observed between the two (Table 6-2). The mean, SD and ES of all jump variables are described in Table 6-2 which compares BEST and WORST. Both the eccentric and concentric phases of movement were significantly shorter in BEST than WORST. This is logical given that contact time is used within the calculation of RSI, however the difference was much more pronounced in the eccentric phase where there was a large significant difference. Despite shorter duration the impulse in each phase was the same or greater in BEST. The greater impulse, despite a shorter timeframe, was achieved through large differences in ECC RFD and leg stiffness thus enabling a rapid production of large forces. Following these altered characteristics in the eccentric phase the BEST jumps achieved greater concentric force, peak concentric power and jump height.

Table 6-2 - Summary of BEST vs. WORST Performance Variables

	BEST	SEM	WORST	SEM	ICC	ES	P
Ecc imp (N/kg.s)	2.78	0.01	2.80	0.01	0.99	2.0	<0.001
Con imp (N.kg.s)	3.34	0.17	2.93	0.22	0.96	2.1	<0.001
Ecc phase duration (ms)	60	6	140	21	0.87	5.2	<0.001
Con phase duration (ms)	120	10	170	30	0.95	2.2	<0.001
Ecc RFD (N.kg.s^{-1})	720	248	163	52	0.96	3.1	<0.001
Leg Stiffness (N.kg.m^{-1})	10.7	1.9	4.31	1.2	0.63	4.0	<0.001
Peak Ecc Fz (N/kg)	91	8.1	71	13.9	0.88	1.8	<0.001
Peak Con Fz (N/kg)	63	8.9	36	3.6	0.96	4.0	<0.001
Peak Ecc Power (W/kg)	18.3	6.8	24.7	4.7	0.54	1.1	<0.001
Peak Con Power (W/kg)	115	4.3	75	5.2	0.95	8.4	<0.001
Jump Height (m)	0.59	0.1	0.46	0.1	0.90	1.3	<0.001
Contact Time (ms)	190	20	320	50	0.93	3.4	<0.001
RSI	3.08	0.11	1.49	0.11	0.93	14.5	<0.001
Velocity at take-off (m.s^{-1})	3.38	0.18	3.20	0.22	0.92	0.9	<0.001
Force at zero velocity (N/kg)	55.1	12.2	31.6	4.9	0.97	2.5	<0.001
Peak CoM displacement (cm)	5.0	2.6	12.7	7.0	0.90	7.1	<0.001

Ecc imp = eccentric impulse, Con imp = concentric impulse, Ecc RFD = eccentric rate of force development, Peak ecc fz = peak eccentric force, peak con fz = peak concentric force, Peak CoM displacement = peak centre of mass displacement, RSI=reactive strength index, SEM= standard error of mean, ES = effect size. ICC= intraclass correlation coefficient

TPA of displacement-, velocity-, power-, force-time and force-velocity curves were compared between groups to identify areas of non-overlapping 95% CI in accordance with the methods of McMahon et al. (2016). These are denoted shaded areas within Figure 6-2 - Figure 6-6. The centre of mass displacement is illustrated in Figure 6-2. TPA results revealed differences in 95% CI limits throughout the entire movement. The depth of CoM descent in the WORST was around double that of BEST. Velocity of CoM is illustrated in Figure 6-3. These data demonstrate a greater negative velocity of movement in BEST vs. worst for the first 3-10% of the movement. Thereafter, for 16-100% of the movement velocity was greater in BEST (i.e. initially smaller negative velocity and subsequently greater positive velocity) in comparison with WORST. The shorter eccentric phase is also evident through the earlier

achievement of zero velocity in BEST (zero velocity reached at 35% movement time in BEST, 45% of movement time in WORST). Figure 6-4 illustrates the force-velocity curve and highlights the greater vertical force at zero velocity in BEST vs WORST. Figure 6-5 illustrates relative power outputs throughout the movements. Negative power during the braking phase was briefly greater in WORST (3-5% movement time) followed by a prolonged period of greater braking power in BEST (6-22% movement time). Concentric power was then greater in BEST for most of the concentric phase (32-82% of movement time) before reducing toward the end of the movement and falling below WORST (85-100% movement time). Force-time curves are illustrated in Figure 6-6 demonstrating the greater relative force in BEST from 6-75% of movement time. In a pattern similar to that observed in relative power, force decreased in BEST in comparison with WORST toward the end of the movement (79-100% movement time).
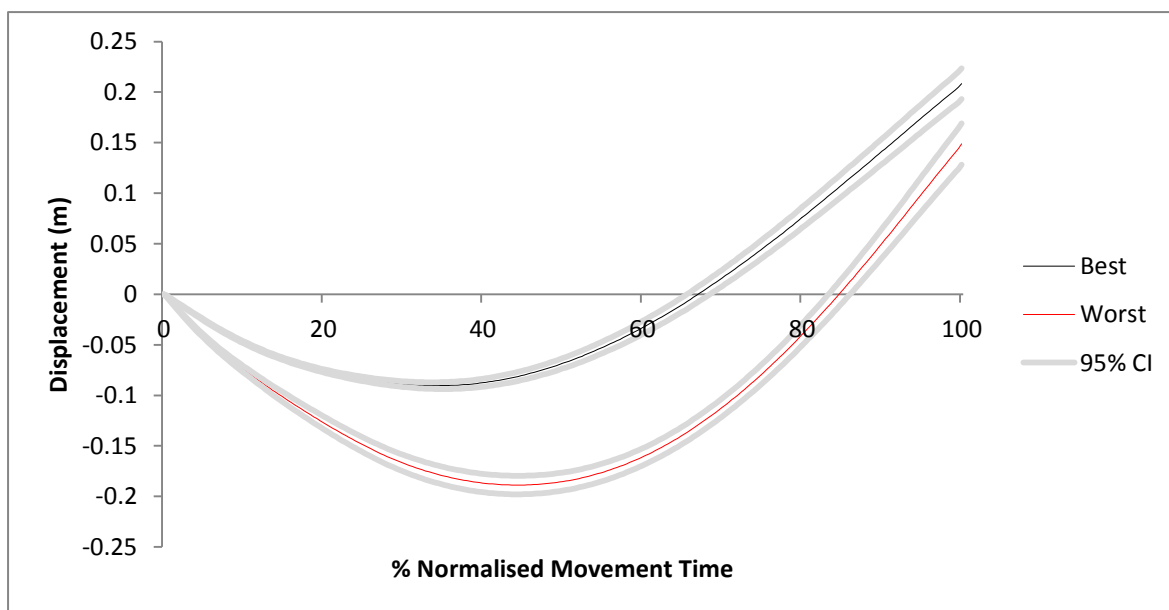
Figure 6-2 - Centre of Mass Displacement
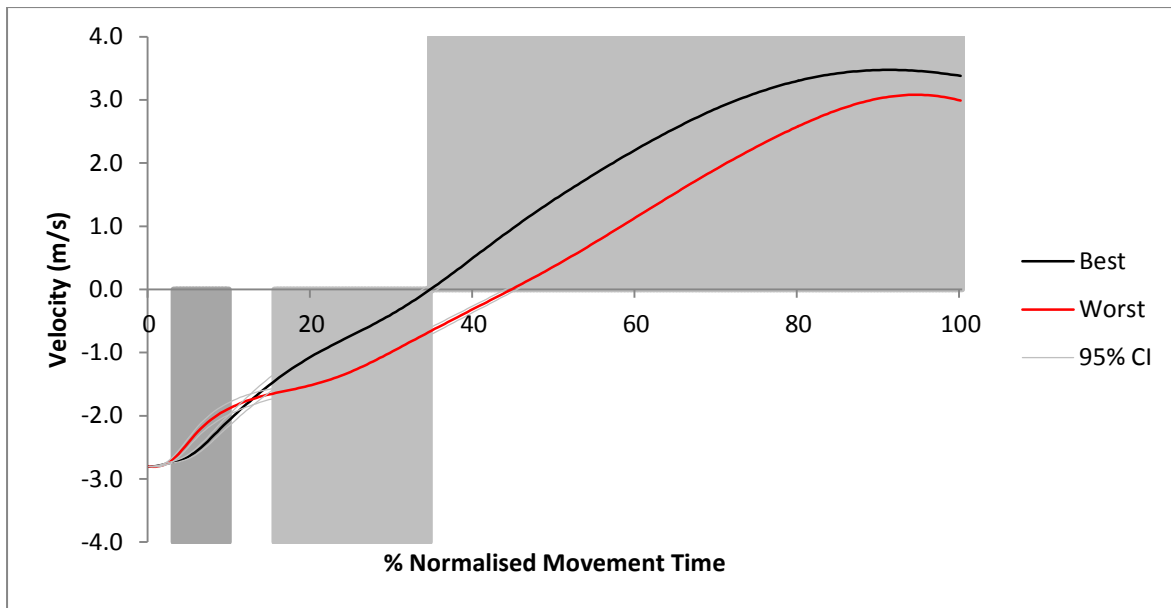
Figure 6-3 - Centre of Mass Velocity
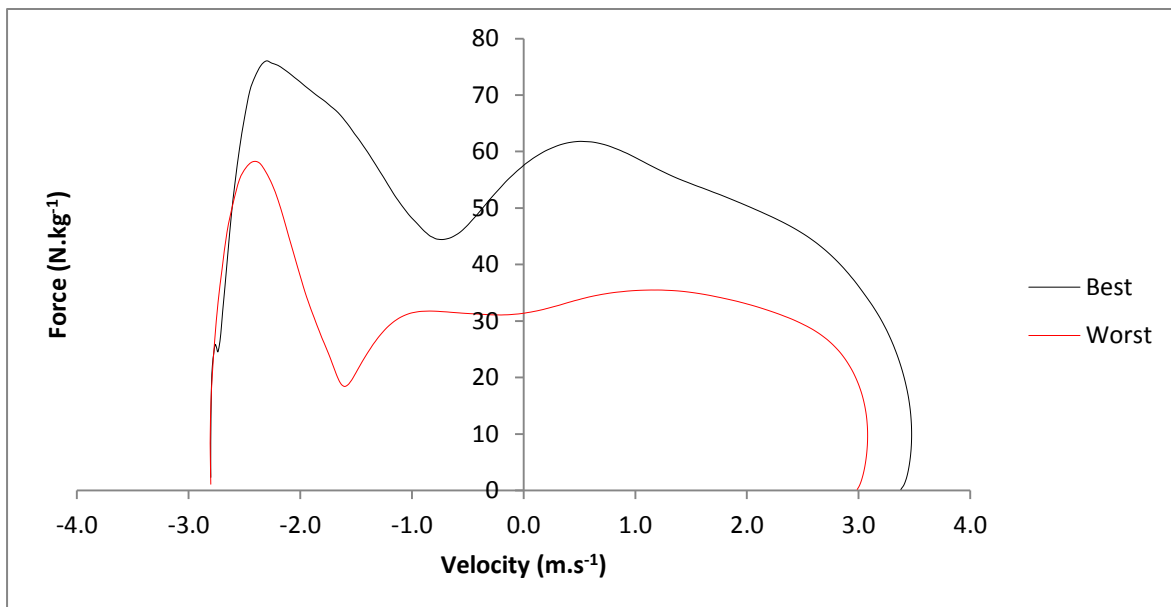
Figure 6-4 - Force-Velocity Curves
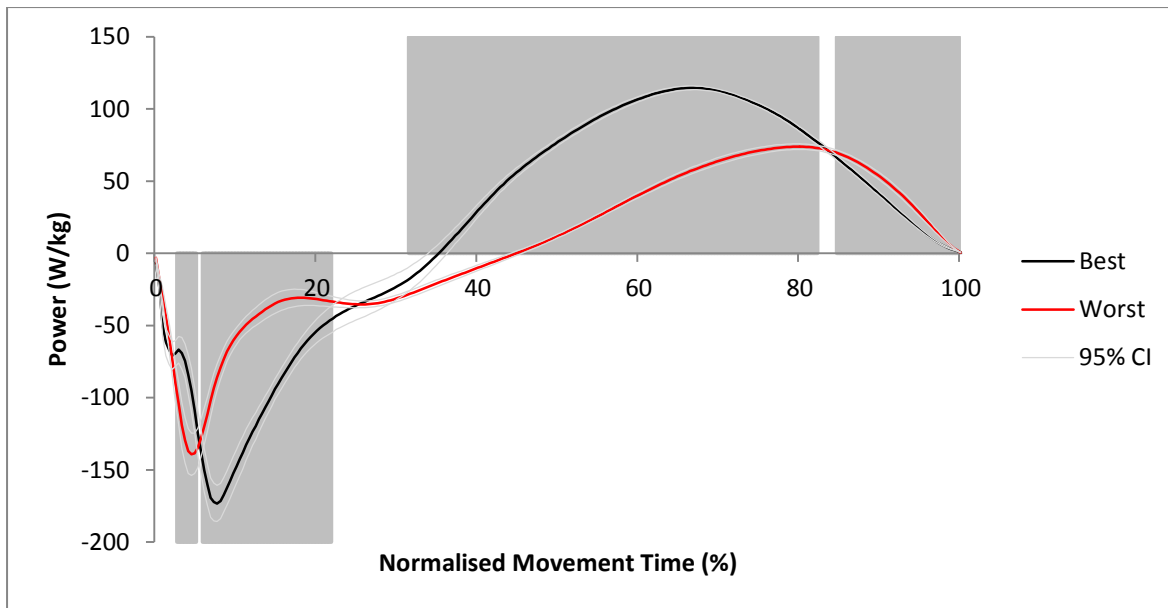
Figure 6-5 - Relative power output
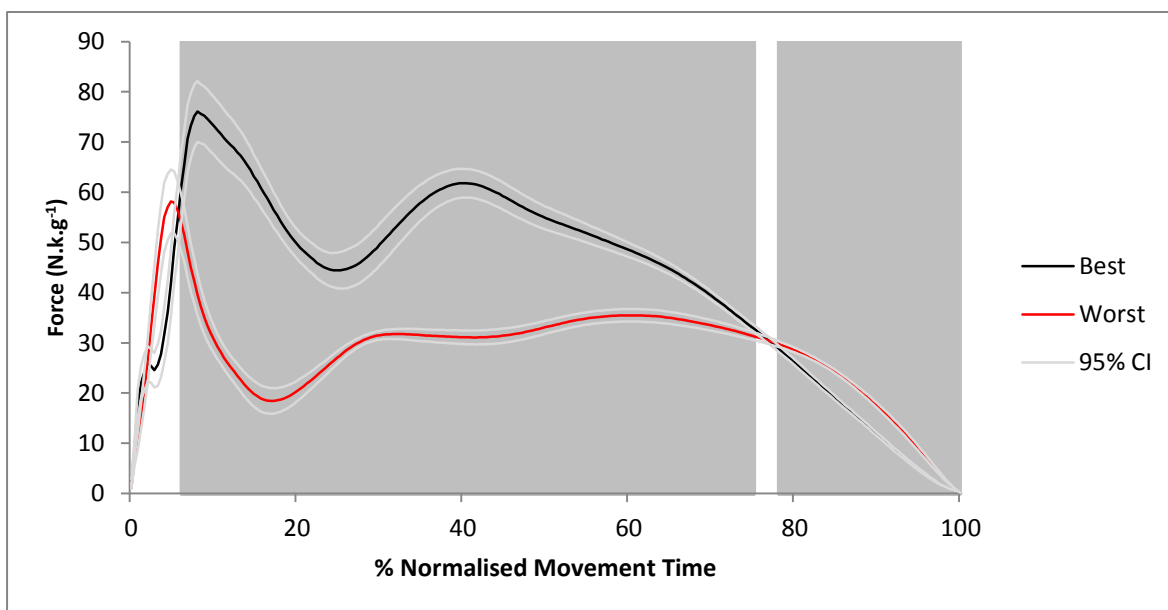
Figure 6-6 - Force-Time Curves

6.6 Discussion

To the author's knowledge, this is the first study to use a TPA approach to assess plyometric exercise performance (i.e. a jump task involving a rebound impact). The key finding of this study is that, in comparison with the traditional reporting of gross measures, the TPA provides a greater degree of insight into the mechanical characteristics of effective

plyometric jumping in the drop jump exercise. This confirmed the hypothesis that jumpers achieved superior results, i.e. greater jump height with shorter ground contact time, by producing similar impulse over a shorter period, especially during the eccentric phase. This manifests in a stiffer landing with a smaller CoM displacement. The jumper gains an advantage through such a strategy as generation of force is increased at the start of the concentric phase and throughout resulting in greater force, velocity, power and displacement.

These findings have important implications for training and performance as they demonstrate the need for athletes to combine the development of neuromuscular capacity to produce force with an effective strategy to apply it to best effect. Further, the findings demonstrate the potential for TPA to clearly distinguish between effective and less effective mechanical characteristics within an elite group. Therefore this represents a powerful tool for diagnostic assessment of performance in high performance sport.

6.6.1   Characteristics of effective jumping

The use of the RSI as the measure of effectiveness considers both the output of the athlete's effort (jump height) and duration over which it was achieved (ground contact time). Environmentally this reflects the nature of the challenge which athletes typically use plyometric exercise to prepare for. For example, a team sport player changing direction to elude an opponent or a high jumper seeking to convert horizontal velocity into vertical. It is only logical that when RSI is used as a measure of effectiveness, a technique which produces the same or greater impulse over a shorter timeframe will appear superior to one performed over a longer time frame. However, in addition to environmental relevance, there is also a strong physiological rationale for favouring a more rapid ground contact in order to maximise the potential for augmented force production via the SSC. The terms "CMJ-DJ" and "bounce-DJ" have been used within the literature to distinguish between distinct techniques which favour either a long contact time and greater depth of descent (CMJ-DJ) or a short ground contact with a smaller depth of descent (bounce-DJ) (Ball and Scurr, 2009, Ball et al., 2010, Byrne et al., 2010, Marshall and Moran, 2013, Struzik et al., 2016, Bobbert, 1990). The WORST jumps within the present study may be considered more

reflective of a CMJ-DJ due to the large ground contact times and greater depth of descent than BEST. However, previously it has been demonstrated that the CMJ-DJ may enable achievements of greater jump heights due to the increased opportunity to apply force during the ground contact (Struzik et al., 2016). This was not the case within the present study as jump heights were inferior for this group. It is noteworthy that subjects self-selected this technique despite instruction to minimize ground contact whilst achieving optimal jump height. This may therefore be a reflection of a lack of technical competency or a deficiency of neuromuscular qualities to achieve such an outcome. It should also be considered that the elite athletes within the present study may possess physical attributes which do not necessitate such a long ground contact time.

Chapter 4 demonstrated that elite athletes achieve superior performance over recreational counterparts during plyometric exercise by producing a greater amount of work over a shorter time frame. The present study demonstrated that the BEST jumps achieved a greater RSI by producing greater impulse to WORST over a shorter duration. This is unsurprising due to the inclusion of ground contact in the RSI calculation. However it is noteworthy that the superior performance was achieved through mechanical characteristics which were not only augmented but also utilised a different pattern of force application. Critically the reduced ground contact time was achieved chiefly through large reductions in both the eccentric and concentric phases although the difference was greater in the eccentric phase. Eccentric phase duration was 57% shorter in the BEST jumps whereas the concentric phase was 29% shorter.

The utilisation of a jump technique which is characterised by a shortened eccentric phase without a loss of impulse is critical to effective jumping. The picture of this technique is further described by a number of other variables. CoM displacement during descent in BEST was around half that of WORST (see Table 2). This is accompanied by a more than two-fold increase in stiffness. These data illustrate a jump technique characterised by a stiff landing with a small amount of displacement performed over a brief window of time. BEST jumps exhibited a greater Ecc-RFD which supports the stiffer technique as braking force is applied more rapidly to counter yielding to the impact forces. Clearly such a strategy can only be

successfully employed provided the athlete has the neuromuscular capacity to tolerate these greater forces.

The movement pattern seen in BEST jumps underpins a number of subsequent kinetic factors which enable an enhanced jump performance. Cormie et al. (2010b) demonstrated that during ballistic jumping, training induced changes in the eccentric phase were correlated with an augmented concentric phase. In the present study this was also evident as force at zero velocity was significantly greater in BEST vs WORST, thus demonstrating that jumpers entered the concentric phase in an advantageous state. Previously, Bobbert et al. (1996a) has described the importance of achieving high active state prior to the onset of the concentric phase when jumping. The rapid nature of the concentric movement in jumping represents a significant time constraint for the production of maximal force. Therefore strategies which enable the generation of high levels of active state and subsequent force generation prior to concentric movement are likely to lead to enhanced performance. This was evident in the present study with a 75% greater relative force being produced at the onset of the concentric phase in BEST. This advantage is continued throughout the movement and results in greater impulse being applied during this phase. Critically, this leads to greater positive movement velocity throughout the concentric phase and at take-off. This represents the conclusion of a chain of events which begins with a brief, stiff landing with a small amount of displacement leading to high levels of isometric force being generated prior to the concentric phase (as reflected in force at zero velocity) and a subsequent augmented peak concentric power output, velocity at take-off and jump height.

Such a technique as that described above is consistent with common coaching methods which place an emphasis on stiff landings and brief ground contact times. However it should be noted that such a performance can only be achieved when supported by the requisite neuromuscular qualities (Beattie et al., 2016). These will include the ability to achieve high levels of pre-activity prior to ground contact, eccentric strength to resist yielding, and the ability to produce a high eccentric-RFD. When utilised during drop jumping these neuromuscular qualities enable a more rapid stretching of tendon tissue during landing and a greater subsequent recoil during propulsion as has been demonstrated previously in drop jumping (Ishikawa and Komi, 2004, Ishikawa et al., 2006, Ishikawa et al., 2005). This is

essentially a classic demonstration of the SSC model and illustrates the importance of neuromuscular capacity to take advantage of tendon recoil in high force activities such as drop jumping.

Cormie et al. (2009) found that following a power training programme subjects improved jump performance and exhibited a modified technique which utilised a greater depth of descent without extending the duration of the phase. The power training programme was composed of a loaded jump squat regime. It could be hypothesised that such a training regime may lead to fascicle lengthening and therefore optimal fibre length may have altered and influenced optimal depth of descent when jumping. Without data to support such a contention it is merely speculation. However the discussion highlights the need to consider the physical qualities of an athlete when evaluating jump technique. Muscle-tendon architecture may influence optimal muscle length and therefore the most effective joint angles and associated descent. Equally a less stiff landing strategy which allows greater yielding may be used to increase the duration of the concentric phase as an alternative strategy for increasing concentric impulse (McMahon et al., 2017a, Jidovtseff et al., 2014a). Whilst such a strategy would be likely to have a diminished contribution from elastic energy following tendon recoil, such benefits are only available when an athlete has the strength qualities to resist high forces as discussed within Chapter 4.

6.6.2 Practical Applications.

Gross measures of plyometric performance, such as peak power and jump height, have been used effectively as a measure of performance and neuromuscular status in plyometric exercise. Such measures enable quantification of performance outcome and distinction between better or worse performances. The RSI can be considered more insightful than measuring jump height alone as the timeframe of force application is also considered and therefore understanding of how jump height was achieved is increased. The use of TPA to assess plyometric exercise continues this interrogation of the question "how" and provides valuable insight into the mechanical characteristics of a jump. Until fairly recently, plyometric performance gains following training have generally been regarded as representing an upregulation of neuromuscular qualities. The present study extends the

findings of Cormie et al. (2009) and Cormie et al. (2010b) from ballistic to plyometric exercise and demonstrates that enhanced performances are achieved through a combination of an altered mechanical strategy and the neuromuscular qualities required to support it. Consequently TPA has significant potential as a diagnostic tool to enable coaches and sports science practitioners to evaluate whether training should be directed toward altered technique to make better use of existing neuromuscular qualities or developing these qualities where technique is deemed to be optimal. Further research is required to identify population norms to enable such judgements. Whilst these findings support the use of a detailed interrogation of ground reaction forces to gain insight into plyometric performance they also validate the use of RSI in a practical setting. This represents a simple measure which relates to a number of kinetic variables underpinning jump performance.

6.6.3 Limitations

The use of a drop jump represents one of the most commonly used plyometric exercises in training. The evaluation of this exercise alone is a limitation when considering plyometric exercise more broadly. Alternative plyometric challenges such as unilateral, horizontal and multi-directional should also be evaluated before extrapolating the findings of the present study. The use of varied sample frequencies should be addressed in future studies with a recommendation of a minimum of 2000 Hz for ground contacts of 250 ms and above although higher frequencies are required for shorter contacts in order to ensure at least 500 samples during the TPA.

Finally, the peak values attained during analysis were based on dividing the movement into concentric and eccentric phases. This is a less detailed approach than that applied in the previous chapter whereby the eccentric phase was subdivided into impact and eccentric components. This was due to the opportunity to gain greater insight through TPA rather than a detailed analysis by phase. However use of such an approach may be applied in future studies comparing performances between groups.

6.6.4 Summary

This study demonstrates for the first time that TPA offers novel insight into the mechanics underpinning plyometric exercise and may be used to distinguish between jumps within an elite athletic group. This analysis describes a technique characterised by a brief and stiff landing phase leading to enhanced force, velocity and power during propulsion.

Chapter 7 - Discussion

7.1 Overview

This chapter presents a summary discussion of the key findings of this thesis. From a scientific perspective this will include discussing the limitations of the present research as well as suggesting areas of future enquiry. Significant consideration is also given to the practical application of these findings as jumping can be considered an inherently applied topic of study.

7.2 Introduction

The genesis of the line of enquiry within this thesis was an observation as an applied practitioner that a significant gap seemed to exist between plyometric training guidelines within the literature and the effects observed when working with athletes. Training guidelines consistently describe plyometrics as high intensity exercise likely to induce significant fatigue and require several days of recovery. Whilst elite power athletes commonly exhibited such effects, the experience of the author with other elite populations such as team sport players was very different. In practice, these athletes seemed able to perform plyometric exercise in large volumes with seemingly little recovery required. This perhaps reflects the fact that current guidelines still emanate from the findings of Russian coaches working with speed and power athletes in the mid-twentieth century.

To date, the current literature has, for the most part, failed to address this gap in understanding between how this niche population of speed-power athletes may differ from other athletes and non-athletic populations and any implications for training prescription. Studies have typically relied upon recreational athletes and differences between this general population and their elite counterparts is rarely discussed, if at all. This may partly be due to the absence of a consensus methodology for the quantification of the training dose in such exercises. This thesis addresses both these issues by first evaluating the methods of

describing volume and intensity of jump exercises and then by applying the methodology to an elite athlete population.

This thesis is characterised by the use of elite athletes. The contrast of these findings with recreational counterparts provides critical insights which carry potentially profound implications for the applied prescription of plyometric and ballistic exercise. Furthermore, the level of performance displayed by the athletes within this thesis is rare if not unprecedented within the literature. This, combined with an assessment of kinetic and kinematic characteristics which underpin these performances, provides researchers and practitioners with novel and valuable insight into this important training methodology.

7.3   Measures of Intensity in Plyometric and Ballistic Exercises.

This thesis began by evaluating methods of quantifying jump exercise volume and intensity. This was considered in terms of "internal loading", as represented by muscle activation, and "external loading" as represented by kinetic variables. When using muscle activation as a means of quantifying plyometric intensity, concentric muscle activity did not differ between exercises in either VL or BF. Eccentric muscle activity was significantly greater in plyometric exercises than ballistic exercises in VL and BF. The finding that this methodology only distinguishes between eccentric actions in ballistic versus plyometric exercises provides utility from a number of perspectives. Firstly, it is clear that such an approach does not provide the level of sensitivity required to evaluate intensity of this type of exercise even if the practical challenges of its application were removed. The finding of eccentric activity being matched within the classifications of plyometric and ballistic exercises supports the rationale for these groupings. Perhaps more importantly though is the finding that concentric activity was matched across all exercises with no significant differences detected. These types of jump exercise are usually performed with maximum effort or intent. Consequently this leads to the understanding that the "internal loading", i.e. the proximity to physiological maximum effort, is a poor method of distinguishing between exercises. This is in contrast to many other forms of intensity measurement in alternative modes of exercise such as the wide spread use of heart rate and rate of perceived exertion in

endurance exercise and the use of percentages of one-repetition maximum in resistance training.

It is well understood that greater maximal forces can be achieved when working eccentrically than concentrically. The velocity achieved prior to the ground contact in a plyometric exercise, be it from stepping from a box or a previous jump, provides an opportunity to overload the eccentric phase of a jump to a greater extent than is possible in a ballistic exercise. As an athlete makes contact with the ground in such circumstances, ever greater braking forces are required to resist yielding as the drop height and associated velocity increases. Within applied settings, this has traditionally been the basis on which coaches judge intensity, i.e. greater drop height equals greater velocity equals greater intensity. This would appear to be a reasonably effective practice given the finding that the magnitude of kinetic challenge ("external loading") is the most appropriate descriptor of intensity. However such a rationale only holds true to the point at which an athlete is able to take advantage of the increased loading. If the demands of the task exceed the athlete's functional capacity to produce eccentric force then the kinematics of the exercise, such as depth of descent or duration of ground contact, will be altered along with the kinetic profile. It is for this reason that it is recommended the term "intensity opportunity" be adopted.

Use of the term, "intensity opportunity" with training literature would, for the first time, acknowledge that the intensity of a plyometric challenge is a product of both the exercise demands and the athlete themselves. It is for this reason that it is argued that a given plyometric exercise could not be described as high intensity per se. It is accepted that highly skilled coaches are able to sensitively detect subtle differences in technique such as longer ground contacts or an increase in yielding and adjust challenges accordingly. The development of the "coaching eye" is an important skill which should not be discarded in favour of automation with kinetic profiling. However the use of such data may serve to compliment the more subjective judgement of a coach and, in junior and developing coaches, may actually serve to accelerate the development of the ability to perceive such phenomenon visually. Intensity opportunity is a novel term which has not been previously observed or acknowledged within the research literature, training guidelines, or common coaching practice. Consequently this represents a novel and important finding from this thesis. Practitioners are encouraged to use ground reaction force data to assess the

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intensities achieved by athletes. Where this is not available, use of the data within this thesis, which has explored various elite and non-elite athlete groups, may serve as a useful guide to likely PF during a variety of plyometric and ballistic exercises.

7.4 Volume in Jump Activity

Relatively little focus within the literature has been placed on the measurement of volume in jump exercise. The finding within Chapter 3 that impulse, or relative impulse if comparing individuals, may be the metric best suited to describing this aspect of training provides a scientific underpinning for a useful applied methodology. As discussed previously, volume comparisons need to also consider the magnitude of forces involved if meaningful conclusions are to be drawn. It is suggested that a practical means of doing so may be through the creation of "intensity bandings" within which comparison of accumulated impulse could be considered sufficiently homogenous to assume parity. An arbitrary starting point for such a system may be the use of number of BW within the intensity of an exercise as a banding system. For example, impulse accumulated during activity with a PF of 3.5 x BW would be compared with other activities within the range of 3.0-3.9 x BW. Such an approach would mitigate the risk of high volume, low force activities being artificially viewed as representing a comparable stress to low volume, high force actions. The use of impulse as a volume-load measure presents coaches and practitioners with significant utility. The measure of volume-load of jump based exercises has largely been ignored within the literature and methods in practical settings have not moved beyond the counting of repetitions for over half a century. The use of impulse represents a step-change in the degree of precision with which volume-load is measured and also provides a valid methodology for comparisons between exercises. Future research should compare the responses to homogenous bandings, including both the fatigue response and adaptive response, in order to validate discrete categories beyond the arbitrary divisions proposed above.

7.5   Technique & Jumping Nomenclature

Whilst it was not a focus of enquiry within this thesis, in reviewing the literature it is clear that the significance of small changes in joint kinematics and the need to describe techniques performed is often inadequate. Cappa and Behm (2013) demonstrated that small differences in technique, such as a flat foot contact versus the ball of the foot, may have profound implications on the kinetics and muscle activation patterns. Naturally this should be a key consideration for coaches in order to guide athletes toward techniques which are not only safe but maximise the likelihood of achieving the specificity of stimulus required and subsequent outcome. Presently this is a major limitation within the literature as exercises are typically reported with no information regarding the kinematics involved. Early attempts have been made to address this through the use of sub-classifications such as the bounce drop jump or the CMJ drop jump. However these still fall significantly short of providing sufficient information to assume that the kinematics within such a classification will be homogenous. Whilst it represents a methodological challenge, it is recommended that a position consensus be agreed for the best practice reporting of plyometric exercise. This is also a key consideration for the practical coaching of such exercises. Whilst the focus of this thesis has largely centred on the kinetic profile of jump exercises, a failure of coaches to pay close and detailed attention to the kinematics of a movement may dramatically affect the outcome. Equally, it is crucial that coaches establish a clear picture of the desired adaptations to such exercises in order to inform coaching instructions which elicit the desired kinematics.

7.6   Practical Application of Intensity Measurement

Despite the significant increase and reduced cost of force platform technology within applied settings, the collection of GRF data remains unavailable to many. Furthermore the collection of GRF data often presents logistical challenges such as the number of athletes and the task of managing technology whilst coaching. Therefore it is recommended that in such circumstances the findings of this thesis may provide an indication of the likely PF and impulse which athletes of different training background may experience during plyometric

exercise. Alternatively, it may be desirable to conduct a "plyometric screening" at appropriate intervals within the training calendar during which athletes would perform commonly used exercises to assess likely forces generated on an individual basis. Potential reference data can be drawn from recreational athlete data presented in Chapter 3 and Chapter 5, elite track and field data in Chapter 4, Chapter 5 and Chapter 6, and professional team sport athletes in Chapter 5. When viewed collectively these present what may be considered the most important practical finding of this thesis, namely that identical jump challenges are likely to elicit dramatically different kinetic loadings in individuals of different training backgrounds. This is not acknowledged within either coaching or scientific literature. In both settings, performance enhancement plyometrics (as opposed to submaximal rehabilitation exercises) are almost exclusively described as being very high intensity and requiring significant recovery and low volumes. Such a view emanates from the origins of plyometrics within the Soviet Union in the 1960s (Verkoshansky and Siff, 2009). Whilst this view is supported by the results recorded by elite track and field athletes within this thesis (the training background of whom matches those involved originally in the Soviet Union) it is recommended that significant overhaul be given to guidelines for athletes outside of this group. In the first instance this may involve a re-evaluation of the limits of volume which are typically recommended not to exceed 100 ground contacts per session (Potach and Chu, 2000). Given the relatively low PF seen in recreational subjects within this thesis and in collegiate athletes within the literature, such a precaution may be excessive. For novice athletes volumes may be more appropriately determined according to an ability to maintain form and an appropriate level of skill development stimulus. It may also be desirable to reconsider how such training sessions are constructed with the potential to move away from a contact counting paradigm to an alternative such as working according to duration of training sessions as a measure of volume. It is recommended that those involved with the publication of exercise guidelines consider these findings with a view to significant revisions.

Finally, the use of a methodology within Chapter 4 which considered the distinct phases of a jump when evaluating PF highlights the need to consider the landing phase. Within ballistic exercises this represented a far greater level of intensity than that experienced during the jump itself. Within plyometric exercises the inclusion of the landing phase would generally

result in a realisation that the number of high impact ground contacts is double of that when only the jump itself is considered. The number and magnitude of these impacts can be easily modulated through the use of jump boxes which may remove some or almost all of the impact involved. When coaching jumping technique, coaches should also give close consideration to providing instruction on landing mechanics. This is clearly important from an injury prevention standpoint but may also be beneficial with regard to ensuring that the athlete receives the load in a manner which is likely to lead to a specific targeted adaptation. For example, this phase may be used to promote mechanical stiffness or the skill to return quickly to an athletic position.

7.7   Bilateral versus Unilateral Considerations

A system which enables comparison of the load placed on an athlete during bilateral versus unilateral exercise remains elusive. This presents a significant challenge to those involved in prescribing such exercise as programmes will typically make use of both modalities. In a rehabilitation setting it is common practice to progress from bilateral to unilateral exercises as the ability of an athlete to cope with reduced stability increases. The absence of a bilateral deficit in muscular activation within Chapter 3 is significant in this regard as practitioners and coaches can be reassured that there is no loss in internal loading when using bilateral exercises (assuming they are performed with maximal intent). Whilst it was not a specific focus of enquiry, the application of a weighting factor of 1.21 to unilateral loadings was explored based on a theory of body segment contribution (Graham-Smith et al., 2015). This would appear to have some merit both from the logical rationale and the finding of a ratio of 1.22 and 1.23 in ballistic and plyometric uni-bilateral comparisons respectively. Further research is required to interrogate the validity of such a methodology.

7.8   Kinetic and Kinematic Insights into Effective Jumping

Both within the recent literature and within this thesis it is clear that optimal jumping requires an effective strategy for the application of force as well as the neuromuscular capability to reduce and produce force in large magnitudes. McMahon et al. (2017b)

demonstrated a kinetic profile of effective jumpers characterised by a taller, thinner impulse force profile in comparison with inferior jumpers. A similar observation can be made when comparing impulse between the elite athletes in Chapter 4 with the recreational athletes in Chapter 3. This highlighted that whilst elite athletes produced greater impulse, the scale was much less than that when PF or jump heights were compared. As a consequence it can be concluded that these athletes deployed a strategy which did not rely solely on the physiological capacity to do more work but also on a more effective use of their neuromuscular advantage. Of course, it may be a false dichotomy to attempt to separate neuromuscular attributes from the strategy with which they are deployed. It may be reasonably hypothesised that the greater strength of these athletes enabled a stiffer landing due to higher braking forces resulting in a shorter ground contact and a greater reliance on elastic energy. The use of such a strategy also requires an ability to skilfully anticipate the ground contact and to produce a well-timed response in the form of pre-activation and a rapid production of eccentric force. It is recommended that in order to continually develop such perceptive skills athletes are presented with a wide variety of plyometric challenges to continue to provide overload in this regard. Failure to do so in favour of a purely neuromuscular focus to exercise choice may hinder the development of this important skill which may prove limiting in the field of play during competitive sport when the need to perceive, interpret and respond to a stimulus is often key.

The TPA methodology has become established as a valuable tool for understanding how a CMJ is achieved. It would seem that there are two distinct (although not mutually exclusive) routes to superior performance. The first is through possession of a greater ability to produce concentric force. This seems to be largely mediated by the neuromuscular ability of the athlete. The second is the augmentation of the eccentric phase which has been suggested is a consequence of training and the development of a superior jumping strategy. These specific routes to effective jump performance are described within the literature (McMahon et al., 2017b, McMahon et al., 2016, Cormie et al., 2008, Cormie et al., 2009, Cormie et al., 2010b) and supported by Chapter 5 within this thesis. Significant further research is required to demonstrate consistent observation of these mechanisms and to further test the hypothesis linking each with neuromuscular qualities and training adaptations respectively. On the basis of current understanding of CMJ interpretation,

coaches may wish to consider this as a means of understanding the potential for improvement in an athlete and directing them to the most effective route to enhancement. For example, the absence of a bimodal force-time trace and an augmented eccentric peak may suggest that an athlete has the potential to enhance their CMJ performance by working towards the development of such a strategy. The nature of a training regime designed to achieve this outcome remains unclear and requires further research. It is likely that this requires the development of both neuromuscular capacity and skill. The use of TPA during settings in which CMJ is used as an indication of neuromuscular function may be both novel and potentially valuable. CMJ is often used during athlete screening protocols such as talent identification or as part of the pre-contract medical examination in professional sports. The degree to which an athlete deviates from an augmented eccentric profile may give an indication as to the potential to make improvements. Such an insight may prove at least as valuable as the absolute performance data as within both the aforementioned contexts the capacity to improve is of primary interest. A number of studies have applied the TPA methodology to the challenge of detecting fatigue when using the CMJ to assess neuromuscular function (Gathercole et al., 2015a, Gathercole et al., 2015b, Gathercole et al., 2015c, Rousanoglou et al., 2016). This also represents a tool of significant value in applied settings where insight into the effect of training and competition stimulus on an athlete remains of primary interest whilst also being somewhat elusive due to the multi-factorial nature of fatigue.

The application of TPA in the context of plyometric exercise remains in its infancy with the final study within this thesis being the first time such a methodology has been applied. The finding of better jumpers making greater use of the eccentric phase through a shorter, stiffer ground contact is in-keeping with the empirical view of plyometrics traditionally held by coaches and, in that regard, is unsurprising. Consequently perhaps the most valuable finding from this study is validation of TPA as a means of evaluating plyometric exercise and therefore this provides a platform for further enquiry to interrogate specific questions around the nature of optimal performance and the identification of "kinetic signatures" as has emerged within the ballistic challenge of a CMJ. Furthermore, the use of highly elite subjects within this study, as well as within Chapter 4 and Chapter 5 provides valuable data on this often-elusive group. Such a group may be considered to represent highly elite

jumping performance and therefore provide a gold standard across the various kinetic and kinematic measures described within this thesis.

7.9 Limitations

The biggest limitation of the studies within this thesis is the relative homogeneity of the subject groups. Although specific comparisons were made between distinct populations all subjects were male and of similar age. Consequently further research is required to replicate the findings of this thesis in females as well as youth and older age groups. Chapter 5 compared differing athletic populations (i.e. team sport players with track and field athletes), however there is a need to extend this enquiry to those involved in other sporting activities such as aquatic and endurance athletes who may produce different results.

The findings of Chapter 4, Chapter 5, and Chapter 6 may have been strengthened by the inclusion of measures of neuromuscular qualities such as back squat 1RM to provide an indication of strength. Such an addition would potentially provide insight as to the extent to which performances are the result of superior neuromuscular strength rather than technical differences in jump performance. Furthermore, this may also aid understanding as to the extent to which neuromuscular strength is required to support alternative techniques such as a rapid unweighting phase in a CMJ. Without measures of strength there is a risk of creating a false dichotomy between physical qualities and technique in jumping.

The kinetic variables assessed across this thesis consistently demonstrated high intra-session reliability. However the methodology did not enable an assessment of inter-session reliability. To ensure the robustness of these as reliable measures further investigation to establish inter-session reliability for specific populations is recommended. This should be considered population specific as the ability to reliably reproduce a jump performance may be, to some extent, dependent on familiarity and technical expertise. Consequently it is likely that less experienced jumpers will demonstrate inferior reliability in comparison with more experienced counterparts. It should also be noted that the practice of assuming drop height based on box height is likely to carry a degree of error (Kibele, 1999). Any error in drop height will affect calculations of velocity and displacement and therefore it is recommended that best practice during drop jump assessment should include measures to

accurately measure drop height. It is suggested that video monitoring may be a practical means of reducing this error.

7.10 Summary

The aim of this thesis was to explore and deploy means of describing the kinetics and kinematics of jump exercise in order to address a significant gap within both the research and in practice. Significant progress has been made in this regard with the demonstration of a methodology of kinetic assessment which describes the volume and intensity of jump exercise with a high degree of sensitivity. The novel application of TPA to plyometric exercise also represents a significant progression in the understanding of the evaluation of such exercise. Finally, this body of research describes a number of key insights into the nature of jump performance. The illustration of the varying nature of intensity depending on training status and the introduction of the concept of intensity opportunity is key. Furthermore the support of bi-modal CMJ strategies which are underpinned by either enhanced eccentric or concentric performance further supports an emerging pattern within the literature.

Chapter 8   - References

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