A Biomechanical Analysis of Variations of the Power Clean and their Application for Athletic Development

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TERMS AND ABBREVIATIONS

Clean:	Part of the Olympic lift, Clean and Jerk. The bar starts on the floor, is displaced via extension of the knees, to just above the patella and is then rapidly repositions via a double knee bend and accelerated upwards via a triple extension of the ankles, knees and hips and then caught in a full depth front squat, with a knee angle <90 degrees
CMJ:	Countermovement jump; initiated with a rapid countermovement to stimulate the stretch shorten cycle
COM:	Centre of mass of an object
Forward Dynamics:	Method of calculating power output based on force time data collected using a force plate
GTO	Golgi tendon Organ: Sensory receptor responsible for monitoring tendon length and tension of the tendons
GRF:	Ground reaction force. In this case vertical ground reaction force (vGRF) collected through the use of the force platform.
Hang Power Clean:	A derivative of the power clean, where the bar starts just above the patella and is rapidly repositions via a double knee bend and accelerated upwards via a triple extension of the ankles, knees and hips and then caught in a shallow front squat position, with a knee angle >90 degrees
Inverse Dynamics:	Method of calculating power output based on displacement time data, usually based on barbell velocity
IMTP:	Isometric mid-thigh pull; multi-joint method of isometric assessment of lower limb kinetics
LPT:	Linear Position Transducer; a device which measures displacement time data which permits calculation of velocity, usually of a barbell
Mid-Thigh Power Clean:	A derivative of the power clean, where the bar starts at mid-thigh and is rapidly accelerated upwards via a triple extension of the ankles, knees and hips and then caught in a shallow front squat position, with a knee angle >90 degrees
MTCP:	Mid-Thigh Clean Pull; where the bar starts mid-thigh and is rapidly accelerated upwards via a triple extension of the ankles, knees and hips

MVIC:	Maximum voluntary isometric contraction; method of isometric assessment of lower limb kinetics, usually single joint, e.g. Knee extension
PMax:	Maximal Power Load; the optimal load to elicit peak power for a specific exercise
Power Clean:	A derivative of the clean, where the bar starts on the floor, is displaced via extension of the knees, to just above the patella and is then rapidly repositions via a double knee bend and accelerated upwards via a triple extension of the ankles, knees and hips and then caught in a shallow front squat position, with a knee angle >90 degrees
RFD:	Rate of Force Development
SJ:	Squat jump; Performed from a static position with no countermovement to eliminate the stretch shorten cycle
SSC	Stretch-shortening cycle; where a movement is initiated with a rapid eccentric action to stimulate the muscle spindle and store elastic energy, immediately followed by a rapid concentric action which utilises the neurological potentiation and elastic energy
System Mass:	The mass of an individual and the external load applied to it, (e.g. Body mass + barbell mass)
1-RM:	One repetition maximum; the greatest load that can be successfully lifted for one repetition during a given exercise

ABSTRACT

The aim of this series of studies was to determine the effect of power clean variation (power clean (PC), hang power clean (HPC), mid-thigh power clean (MTPC) and mid-thigh clean pull (MTCP)) and load on force time characteristics, in an attempt to identify the optimal variation and load to develop specific force time characteristics.

Study 1 demonstrated that assessment of peak force, peak rate of force development (RFD) and peak power were highly reliable (ICC $r \geq 0.968$) during the PC, with smallest detectable differences of ≥8.68 N, ≥24.54 N.s, ≥68.01 W, respectively, signifying a meaningful change.

Study 2 and 3 demonstrate that the MTCP and MTPC are preferential in terms of maximising acute kinetic performances when compared to the PC and HPC, as they result in the greatest peak force, peak RFD and peak power.

In contrast, study 4 showed no kinetic differences ($p>0.05$) across PC variations (PC, HPC, MTPC) or load (70, 70, 80% 1-RM) in inexperienced female collegiate athletes.

Study 5 revealed that peak power output during the PC was achieved at a load of 70% 1-RM, although this was not significantly ($p>0.05$) different when compared to the 60% and 80% 1-RM loading conditions, in inexperienced athletes, in line with previous research in well trained athletes.

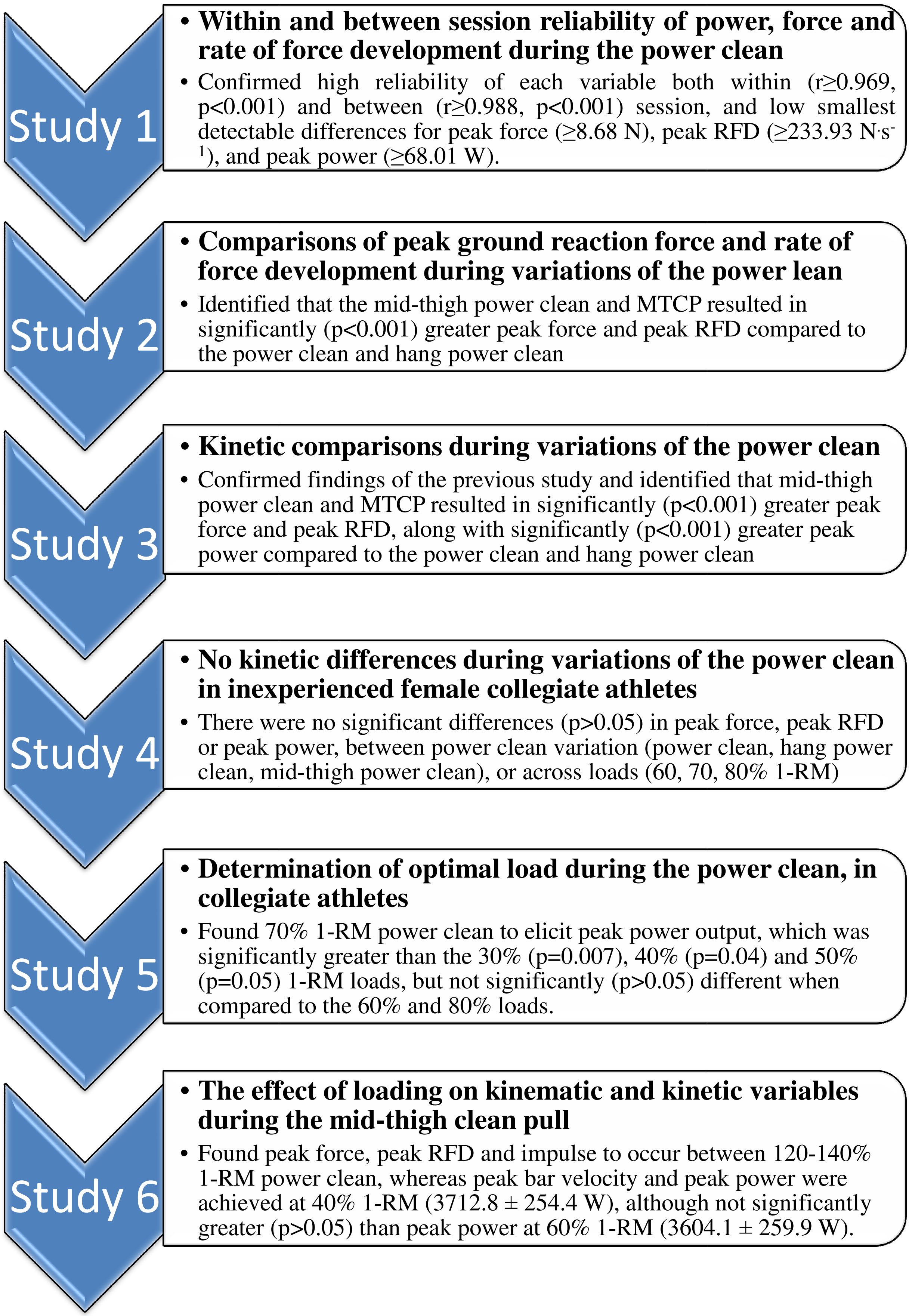
Finally, study 6 demonstrated that when the MTCP is performed with loads of 120-140% 1-RM PC, significantly greater peak force ($p<0.001$), peak RFD ($p=0.004$) and impulse ($p \leq 0.023$) occur when compared to loads ≤100% 1-RM. In contrast, significantly greater peak power ($p \leq 0.02$), bar displacement ($p \leq 0.02$) and bar velocity ($p<0.001$) occurs when performed at a load of 40-60% 1-RM.

When incorporating the MTCP into different training mesocycles, it would be useful to use heavier loads during the strength phases, progressing from 120-140% 1-RM PC, to maximise force production and RFD. In contrast, during power mesocycles, it would be advantageous to progressively reducing load to 40-60% 1-RM PC, to elicit the greatest peak power possible during the MTCP or MTPC.

OVERVIEW AND PROGRESSION OF STUDIES

1 OVERVIEW AND PROGRESSION OF STUDIES

The Olympic lifts and their derivatives are regularly included in strength and conditioning programmes, especially during power mesocycles. The power clean and the hang power clean are probably the most commonly used versions of these lifts, due to the fact that they are generally easier for coaches to teach and athletes to master when compared to the full clean or the snatch. In addition, performance in such exercises has been shown to be related to athletic tasks, such as sprint, agility performance and jump performance (Stone, 1993; Baker, 1996; Stone et al., 2003a; Stone et al., 2003b; Blackwood, 2004; Hedrick and Wada, 2008; Hori et al., 2008).



Study 1

- **Within and between session reliability of power, force and rate of force development during the power clean**
- Confirmed high reliability of each variable both within ($r \geq 0.969$, $p<0.001$) and between ($r \geq 0.988$, $p<0.001$) session, and low smallest detectable differences for peak force (≥8.68 N), peak RFD (≥233.93 $N \cdot s^{-1}$), and peak power (≥68.01 W).

Study 2

- **Comparisons of peak ground reaction force and rate of force development during variations of the power lean**
- Identified that the mid-thigh power clean and MTCP resulted in significantly ($p<0.001$) greater peak force and peak RFD compared to the power clean and hang power clean

Study 3

- **Kinetic comparisons during variations of the power clean**
- Confirmed findings of the previous study and identified that mid-thigh power clean and MTCP resulted in significantly ($p<0.001$) greater peak force and peak RFD, along with significantly ($p<0.001$) greater peak power compared to the power clean and hang power clean

Study 4

- **No kinetic differences during variations of the power clean in inexperienced female collegiate athletes**
- There were no significant differences ($p>0.05$) in peak force, peak RFD or peak power, between power clean variation (power clean, hang power clean, mid-thigh power clean), or across loads (60, 70, 80% 1-RM)

Study 5

- **Determination of optimal load during the power clean, in collegiate athletes**
- Found 70% 1-RM power clean to elicit peak power output, which was significantly greater than the 30% ($p=0.007$), 40% ($p=0.04$) and 50% ($p=0.05$) 1-RM loads, but not significantly ($p>0.05$) different when compared to the 60% and 80% loads.

Study 6

- **The effect of loading on kinematic and kinetic variables during the mid-thigh clean pull**
- Found peak force, peak RFD and impulse to occur between 120-140% 1-RM power clean, whereas peak bar velocity and peak power were achieved at 40% 1-RM (3712.8 ± 254.4 W), although not significantly greater ($p>0.05$) than peak power at 60% 1-RM (3604.1 ± 259.9 W).

Figure 1.1 Progression of studies

1.1 Study 1

Numerous studies have investigated or discussed the most appropriate methods to assess power generated during lower body power exercises, concluding that force time data should be collected using a force platform and power calculated using a forward dynamics approach, based on the impulse momentum relationship (Hori et al., 2006; Cormie et al., 2007a; Cormie et al., 2007c; Cormie et al., 2007b; Hori et al., 2007; Lake et al., 2012). No studies, however, have reported the stability of such measures between testing sessions, or the smallest detectable differences, making it difficult for researchers and strength and conditioning coaches to infer meaningful changes in performance pre and post intervention, or between training or testing sessions. In addition, it was essential to establish the within and between session reliability and measurement error (Study 1) prior to undertaking any further studies.

1.1.1 Summary

The findings of this study revealed that the assessment of kinetic variables (peak force, peak RFD and peak power) were highly reproducible within session ($r \geq 0.969$, $p < 0.001$) and between sessions ($r \geq 0.988$, $p < 0.001$), with very low smallest detectable differences for peak force (≥8.68 N), peak RFD (≥233.93 $N \cdot s^{-1}$), and peak power (≥68.01 W). The results highlight that a change of 0.5%, 2.5%, 2.1% for peak force, peak RFD and peak power, respectively demonstrate a meaningful change during performance of the power clean.

1.2 Study 2 & 3

Variations of the power clean are regularly incorporated into athletes' training regimes, with specific potential benefits hypothesised for each variation of the clean, although many of these theoretical benefits have not been substantiated by empirical evidence. The optimal loads which elicit peak power output for the power clean (Cormie et al., 2007c; Cormie et al., 2007b; Cormie et al., 2007e), hang power clean (Kawamori et al., 2005; Kilduff et al., 2007) and MTCP (Kawamori et al., 2006) have been reported between 60-80% one repetition maximum (1-RM) power clean, although these were generally not significantly different at loads ±10% of the optimal load.

In addition, observation of Olympic lifters revealed that the second pull phase of the clean results in the greatest force (Enoka, 1979; Hakkinen et al., 1984; Garhammer and Gregor, 1992; Souza et al., 2002) and power (Garhammer, 1979; Garhammer, 1980; Garhammer, 1982; Garhammer, 1985). It should be noted, however, that by the time the bar reaches this phase of the lift, it has already gained momentum making it unsurprising that the highest power output, assessed via bar velocity, has been observed during the second pull. In addition, the transition phase (also referred to as the double knee bend) results in an unweighting phase which is similar to the countermovement in a countermovement jump (Garhammer, 1980; Garhammer, 1985; Garhammer and Gregor, 1992) and therefore may increase force production and RFD compared to starting at mid-thigh. No research, however, had compared the peak force or peak RFD, during the power clean, hang power clean (bar held just above the patella in the start position, caught in a semi-squat position) the mid-thigh power clean (bar held mid-thigh in the start position, caught in a semi-squat position) and the MTCP (this is the concentric phase of the mid-thigh power clean without the catch phase) (Study 2). Furthermore, no studies had compared peak power during the power clean, hang power clean, mid-thigh power clean and MTCP to establish which variation of the lift generates the greatest peak power, even though these variations are regularly used by athletes in training (Study 3).

1.2.1 Summary

The results from these two studies are interesting as they imply that the MTCP and mid-thigh power clean are equally effective in generating peak power and may be more beneficial in maximising power development compared to the power clean and hang power clean. As these techniques require less technical competence and only a limited range of motion, they may be able to be performed by inexperienced athletes. Such variations of the clean may permit an enhancement in peak force, peak RFD and peak power, from the time they commence a strength and conditioning programme, without the need to acquire the skill to perform classical Olympic lifting techniques. Furthermore, when athletes' have injuries that restrict range of motion and they cannot perform the power clean or hang power clean, the mid-thigh variations may be an excellent alternative.

1.3 Study 4

The majority of previous research has been conducted using well trained team sport athletes (as with studies 1-3) or Olympic Weightlifters (Haff et al., 1997; Haff et al., 2005; Kawamori et al., 2005; Kawamori et al., 2006; Cormie et al., 2007c; Cormie et al., 2007b; Cormie et al., 2007e; Haff et al., 2008), and therefore the application of these findings to inexperienced athletes is problematic. In addition no studies have investigated the effect of loading or variation of the power clean in female athletes. Furthermore, based on the findings of studies 2 and 3, where the mid-thigh power clean resulted in significantly greater peak force, peak

RFD and peak power, compared to the hang power clean and power clean; it was hypothesised that recreational athletes would demonstrated greater differences in kinetic variables across the variations of the power clean due to the lower level of technical competence required to perform the mid-thigh power clean, thus resulting in greater peak force, peak RFD and peak power, when compared to the power clean and hang power clean (study 4). The effect of loading was also expected to have an effect on the kinetic performance of the variations of the clean, based on the findings of previous research, where lower relative loads resulted in greater peak power due to an increased movement velocity (Kawamori et al., 2006; Cormie et al., 2007c; Cormie et al., 2007e; Hori et al., 2007). It was further hypothesised that the lowest load (60% 1-RM), during the mid-thigh power clean, would result in the greatest peak force, RFD and peak power, in line with previous research (Kawamori et al., 2006) (Study 4).

1.3.1 Summary

The findings of this study imply that loads of 60-80% 1-RM power clean can be used interchangeably without a resultant decrease in kinetic values, in inexperienced female athletes. It is suggested that this be adopted in a periodized manner starting with the lighter loads and gradually progressing to the heavier loads as technique improves. Moreover, the results of this study show that the variation of the power clean (power clean, hang power clean, mid-thigh power clean) does not affect the kinetic performances in inexperienced athletes. It may, therefore, be beneficial to alter the variation of the lift performed during each training session, so that athletes develop competency in each variation of the lift and to prevent monotony within the athletes training programme.

1.4 Study 5

As previously mentioned, the majority of previous research has been conducted using well trained team sport athletes (as with studies 1-3) or Olympic Weightlifters (Haff et al., 1997; Haff et al., 2005; Kawamori et al., 2005; Kawamori et al., 2006; Cormie et al., 2007c; Cormie et al., 2007b; Cormie et al., 2007e; Haff et al., 2008), and therefore the application of these findings to inexperienced athletes is problematic. The aim of study five, therefore, was to identify the optimal load during the power clean in relatively inexperienced collegiate athletes. It was hypothesised that 70% 1-RM would result in peak power output, in line with previous research (Cormie et al., 2007c; Cormie et al., 2007d).

1.4.1 Summary

The results of study 5 revealed, as hypothesised, that peak power output was achieved at a load of 70% 1-RM, although this was not significantly ($p>0.05$) different when compared to the 60% and 80% loads, which is in line with previous research in well trained athletes (Cormie et al., 2007c; Cormie et al., 2007d).

1.5 Study 6

Based on the findings of study 2 and 3, where the mid-thigh variations of the clean, more specifically the MTCP, resulted in the greatest peak force, peak RFD and peak power, the effects of load during the MTCP was investigated. The MTCP was of interest as it is simple to learn and does not require a catch phase which can be problematic in injured athletes, and athletes who struggle to disassociate movement when rapidly changing from the concentric phase of the pull to the rapid eccentric phase of the descent into the catch phase. Additionally, as the catch phase of the power clean is omitted during the MTCP, it is possible to use loads that are greater than 100% of the 1-RM power clean. The aim of study 6 therefore was to identify the effects of loading (40-140% 1-RM power clean) on kinematic and kinetic variables during the mid-thigh clean pull. Based on the force velocity relationship it was hypothesised that the lowest load (40% 1-RM) would result in the highest bar velocity and greatest peak power and that the heaviest load would result in the greatest peak force and peak RFD.

1.5.1 Summary

The findings of study 6 revealed that the heavier loads, of 120-140% 1-RM power clean, resulted in the greatest peak force, peak RFD and impulse and that the lightest load (40% 1-RM) resulted in the highest bar velocity and greatest peak power, as hypothesised. It is therefore suggested that the MTPC may be effective at developing both speed strength (40-60% 1-RM) and strength speed (120-140% 1-RM) if appropriate loading is applied. This loading should be applied in a periodized manner appropriate to the athletes' specific goals.

1.6 Conclusions

It appears that the MTCP and mid-thigh power clean are preferential in terms of maximising acute kinetic performances compared to the other derivatives of the power clean (power clean and hang power clean), as it results in the greatest peak force, peak RFD and peak power, when performed at a comparable load (Figure 1.1). A load of 40-60% 1-RM power clean appears to be optimal in terms of peak power during the MTCP, although <40% 1-RM was not assessed. Moreover, as the MTCP does not include the catch phase of the power clean, it permits a load greater than 100% 1-RM power clean to be used, which at 120-140% 1-RM power clean, results in greater peak force, peak RFD and impulse, when compared to loads ≤100% 1-RM power clean (Figure 1.1). To further elucidate the possible advantages of such variations in the performance and loading of these exercises a training intervention study is recommended.

It should be noted however, that the other variations of the clean do have their advantages, and should be used accordingly. In general, the power clean permits athletes to uses heavier loads than the other versions of the power clean which include the catch phase, as the bar is displaced further permitting additional time for force to be applied to the bar, resulting in greater acceleration and therefore peak height of the bar, which results in a successful catch with a higher load. The hang power clean, begins with a countermovement where the knees slide back under the bar, which is suggested to train the stretch shorten cycle (Enoka, 1979; Isaka et al., 1996), although more research is required to substantiate this claim: if this were true it would be feasible to expect that the power output would be greater than during the mid-thigh versions of the exercise. In addition, the power clean and the clean incorporate the transition phase and also exhibit a force time curve which represents an unweighting phase similar to that of a countermovement jump (Garhammer, 1980; Garhammer, 1985; Garhammer and Gregor, 1992). It is also worth noting that the catch phase of the power clean may be useful in training general athleticism of athletes as it relies on a rapid transition from rapid high force concentric muscle action (pull phase) which takes 0.66-0.76 s (Garhammer, 1985), to rapid lengthening of the muscles (rapid descent phase) lasting 0.32-0.38 s (Garhammer, 1985), followed by a rapid isometric muscle action (catch phase).

INTRODUCTION

2 INTRODUCTION

Power is an essential component of sports performance, not just in short duration explosive activities (e.g. sprinting, jumping and throwing events) but also during decisive moments in team sports (e.g. acceleration, change of direction and jumping) (Gabbett et al., 2011c; Gabbett et al., 2011a; Gabbett et al., 2011b). The development of power within an athletes' training programme is therefore essential, however, there are a variety of methods including strength training, ballistic training, plyometric training and Olympic lifts which are commonly used to increase power output (Stone, 1993; McBride et al., 2002; Hansen et al., 2003; Stone et al., 2003a; Cormie et al., 2007d; Harris et al., 2008; Cormie et al., 2010b; Cormie et al., 2010a; Cormie et al., 2011b) with no clear consensus regarding which method or mode of training is optimal. What is clear is that there are moderate to strong associations between power output and athletic performance in sports specific tasks (Cronin and Hansen, 2005; Harris et al., 2008; Harris et al., 2010b; Gabbett et al., 2011c; Lopez-Segovia et al., 2011; Marques et al., 2011; Requena et al., 2011; Cunningham et al., 2013; Sekulic et al., 2013). Moreover, power output is one of the key determinants of tackling ability in rugby league (Gabbett et al., 2011a; Gabbett et al., 2011b) and more importantly match performance in rugby league (Gabbett et al., 2011c).

2.1 Methods of Training used to Enhance Power Output

2.1.1 Strength Training

Strength training usually consists of compound (multi-joint) exercises performed with relatively high loads (85-95% of one repetition maximum (1-RM)), for 4-6 sets per muscle group of 2-6 repetitions, with a 3-5 minute rest between sets 2-3 days per week (Baechle et al., 2008). With differences in the optimal intensity, sets, repetitions and frequency identified for previously untrained (60% 1-RM, 4 sets, 3 days per week), recreationally trained non-athletes (80% 1-RM, 4 sets, 2 days per week), and trained athletes (85% 1-RM, 8 sets, 2 days per week) (Peterson et al., 2004; Peterson et al., 2005).

Possibly the most commonly performed and extensively researched exercise for the development of lower body strength is the back squat, with a number of studies finding moderate to strong associations between maximal strength (1-RM) and short sprint performance (Baker and & Nance, 1999; Wisloff et al., 2004; McBride et al., 2009; Requena et al., 2009; Requena et al., 2011; Comfort et al., 2012a; Kirkpatrick and Comfort, 2012), and three repetition maximum back squat (3-RM) and 10 and 30m sprint performance (Baker and & Nance, 1999; Brechue et al., 2010; Lockie et al., 2011; Comfort et al., 2013b; Cunningham et al., 2013).

While such observational studies have found correlations between maximal back squat strength and short sprint performance, this does not demonstrate cause and effect, however research has also demonstrated that as maximal back squat strength increases there is a concomitant increase in sprint performance, indicated by a decrease in sprint times over 5, 10 and 20 m (Comfort et al., 2012b). Such findings must still be viewed with some caution as the participants in the study by Comfort et al. (2012b) were also performing their ‘normal’ sprint, agility and power training during this period and therefore the improvement in sprint performance may not only be attributable to the increase in back squat strength. In terms of ecological validity, however, this study does demonstrate what actually happens in professional team sports, where confounding variables cannot be eliminated from research.

Additional research, in soccer players, has also demonstrated improvements in sprint performance and change of direction associated with increases in squat strength (Helgerud et al., 2011; Keiner et al., 2013). Similarly, Nimphius, McGuigan and Newton (2012) also found improvements in sprint and change of direction performance along with increases in relative strength during the competitive season, in female softball players. In contrast de Villarreal (2012) found no change in sprint performance even though they observed an increase in strength and power after 7 weeks of training; however, the subjects were relatively weak to start with and therefore the increases in strength may have been predominantly neurological and therefore not transferred to sprint performance within the duration of the study.

Greater maximal strength levels are also associated with greater power output (Baker and Nance, 1999; Baker, 2001; Baker et al., 2001; Stone et al., 2003a; Cormie et al., 2007d; Nuzzo et al., 2008; Cormie et al., 2010b; Cormie et al., 2010a; Cormie et al., 2011b). Baker and Nance (1999) demonstrated a strong correlations (r=0.79) between 3-RM back squat performance and squat jump performance, and even stronger correlations between 3-RM back squat performance and hang power clean performance (1-RM), in elite rugby league players. Nuzzo et al (2008) reported similarly strong correlations (r=0.945) between 1-RM back squat and power clean performances (1-RM), 1-RM back squat and vertical jump performance (r=0.836) and 1-RM power clean and vertical jump performance (r=0.856). Even though power was not assessed in these studies (vertical jump height was used as an indicator of peak power output). A higher power output is associated with an increase in load lifted by Olympic lifters during the Olympic lifts (Garhammer, 1980; Garhammer, 1985; Garhammer, 1991), with similar kinetics observed between the concentric phase of the hang snatch and vertical jumping (Garhammer and Gregor, 1992; Canavan et al., 1996).

Furthermore, Stone et al. (2003a) observed that stronger athletes (1-RM = 2.00 ± 0.24 kg/kg) generated much higher peak power during the countermovement jump (CMJ) (5079 ± 2363 W vs. 3785 ± 376 W) and SJ (5464 ± 2507 W vs. 3842 ± 443 W), when compared to weaker athletes (1-RM = 1.21 ± 0.18 kg/kg).

In a study of relatively weak subjects, Cormie et al (2010a) reported greater improvements in strength after 10 weeks of training, in the strength training group (75-90% 1-RM) compared to the power trained group (0-30% 1-RM), highlighting the benefits of strength training for increasing strength development; although both groups showed similar improvements in jump and sprint performance. While another study by the same authors showed similar improvements in athletic performance in relatively strong (1-RM/BM = 1.97 ± 0.08 kg/kg) and relatively weak groups (1-RM/BM = 1.32 ± 0.14 kg/kg) after 10 weeks of power training (0-30% 1-RM), although they noted a tendency towards greater improvements in the strong group (Cormie et al., 2010b). It is important to note, however, that both of these studies used low load high velocity power training (0-30% 1-RM), rather than the higher loads (80-95% 1-RM) usually recommended for power development during Olympic style lifts (Baechle et al., 2008). In addition, Baker et al. (2001) previously demonstrated that stronger athletes tend to achieve peak power, during squat jumps, at a lower percentage (51%) of their 1-RM back squat compared to weaker athletes (55%), which is in contrast to the findings of Stone et al. (2003a) who found that stronger athletes achieved peak power at 40% 1-RM compared to weaker athletes who achieved peak power at 10% 1-RM. It should be noted, however, that both of these studies calculated power using inverse dynamics, based on bar velocity, which has been shown to alter both the power output and the load that elicits peak power (Cormie et al., 2007a; Cormie et al., 2007c; Hori et al., 2007; McBride et al., 2011; Lake et al., 2012) (Discussed in detail in Chapter 3.1). In contrast to the previous findings, Cronin et al. (2000)

reported that the participants relative strength only influenced initial power production (≤200 ms) during stretch shorten cycle movements and not those performed from a static position without a prior eccentric stimulus, however, this was during the bench press.

One of the problems with training power through normal strength training modes is that the load has to be decelerated at the end of the range of motion, resulting in an altered force velocity profile when compared to ballistic exercises where no deceleration is required. During traditional strength training exercises, such as the back squat, this deceleration phase can account for as much as 45% of the entire range of motion, although this decreases as load increases (Newton et al., 1996). Swinton et al. (2011b), however, found that the inclusion of chain resistance permitted greater force across a greater range of the concentric phase, with a significant increase ($p<0.05$) in peak force and impulse, although in contrast velocity, power and rate of force development decreased significantly ($p<0.05$), as would be expected with a load that progressively increases throughout the range of motion. Baker and Newton (2009) found that substituting 10% of the load with chains during bench press resulted in a higher bar velocity compared to traditional loading, with a further study revealing an increase in power output during the bench press performed with 10% of the load from chain resistance (Baker, 2009). In contrast, when comparing squats performed at 80% 1-RM, using standard plate loading, band or chain resistance, Ebben and Jensen (2002) reported no significant differences in ground reaction forces or surface electromyography across loading methods, with McCurdy et al., (2009) reporting no difference in bench press performance between plate loading and chain loading, after 9 weeks of strength training. Swinton et al. (2011b) may have observed differences in kinetics when using chains compared to plate loading as the chains represented 20% and 40% of the subjects' 1-RM, whereas most other investigations have only used ~5% (Ebben and Jensen, 2002; Coker et al., 2006; Berning et al., 2008; McCurdy et al., 2009), which may explain the difference in the findings and the lack of differences observed between traditional plate loading and the inclusion of chain loading in most studies.

Maximising strength levels has been shown to be more beneficial than high velocity power training in athletes with relatively low strength levels (those that can squat <1.9 x body mass as barbell mass), whereas higher velocity power training in relatively strong athletes (those that can squat ≥1.9 x body mass as barbell mass) appears to be more beneficial than focussing on strength development (Cormie et al., 2010b; Cormie et al., 2010a). In contrast however, Fatouros et al., (2000) reported that weight training combined with plyometric training resulted in significantly greater improvements ($p<0.05$) in jump performances than weight training alone, however, the weight training had a muscular endurance focus (8-12 repetitions per set) rather than a strength focus. It is not surprising that group that performed jumping activities in their training demonstrated greater improvements in jump performances due specificity of training. There were, however, no significant differences ($p>0.05$) in squat or leg press strength between groups.

Based on the findings of the aforementioned studies, it would appear that the initial focus for power training should be to maximise strength levels until the individual is relatively strong (back squat ≥1.9 x body mass) while simultaneously developing technique for ballistic training, plyometric training and Olympic lifts. Once a good relative strength level is achieved greater emphasis should be placed on higher velocity movements such as ballistic training, plyometrics and Olympic lifting, while maintaining or continuing to develop maximal strength levels.

2.1.2 Ballistic Training

Ballistic training usually consists of more dynamic versions of strength training exercises (speed squats and deadlifts), ideally with no deceleration phase during the final stages of the concentric phase, as with squat jumps and bench throws (Newton et al., 1996; Swinton et al., 2011a; Swinton et al., 2011b; Swinton et al., 2012). During such power based training loads of 75-95% 1-RM, for 3-5 sets of 1-6 repetitions have traditionally been recommended (Baechle et al., 2008). Numerous studies, however, have identified that the optimal loads to elicit peak power output for such exercise is substantially lower (Baker, 2001; Stone et al., 2003a; Cormie et al., 2007a; Cormie et al., 2007c; Cormie et al., 2007b; Cormie et al., 2007e; Hori et al., 2007; Cormie et al., 2008; Thomasson and Comfort, 2012) than the loads traditionally recommended for such training, as these guidelines were originally based performances in on Olympic lifts (Baechle et al., 2008).

Baker (2001) demonstrated that stronger athletes utilized a lower percentage of 1-RM (51%) to attain maximal power (PMax) during squat jumps than less strong athletes (55%), although they calculated power based on bar velocity (inverse dynamics) which has been shown to substantially increase the load at which peak power is achieved (Cormie et al., 2007a; Cormie et al., 2007c; Hori et al., 2007; Cormie et al., 2008). In contrast, Stone et al. (2003a) previously reported that peak power output during weighted CMJ and SJ occurred at 40% 1-RM in strong athletes (2.00 ± 0.24 kg/kg) and 10% 1-RM in weaker athletes (1.21 ± 0.18 kg/kg), although they did not assess power in an unloaded (body mass with no external load) condition, and the differences in peak power ± 10% 1-RM either side of these loads were not noticeably different. In addition, power was again calculated based on barbell velocity and barbell mass using an inverse dynamics approach, which has been shown to substantially increase the load at which peak power is achieved (Cormie et al., 2007a; Cormie et al., 2007c; Hori et al., 2007; Cormie et al., 2008) (This is discussed in detail in Chapter 3.1).

Cormie et al. (2010a) conducted a training study with participants training at the individual load which elicited peak power (PMax) in relatively weak subjects, finding greater improvements in strength (31.2 ± 11.3%) in the strength training group after 10 weeks, compared to the power training group (4.5 ± 7.1%). This demonstrates of increasing strength alone, and highlights the specificity of adaptations associated with such training; although both groups showed similar improvements in jump and sprint performance. It is not surprising, however, that the group that performed exercises with the lower loads (0-30% 1-RM) did not demonstrate as great an increase in strength as the group using the heavier loads (75-90% 1-RM). The similar improvements in jump performance may be explained by the fact that both peak force and peak RFD have been shown to be closely associated with vertical jump performances (McLellan et al., 2011b). Another study by the same authors showed similar improvements in athletic performance (sprint and jump performances) in relatively strong (1-RM/BM = 1.97 ± 0.08 kg/kg) and relatively weak groups (1-RM/BM = 1.32 ± 0.14 kg/kg) after 10 weeks of power training (0-30% 1-RM), although they noted a tendency towards greater improvements in the strong group (Cormie et al., 2010b). Similarly, Harris et al. (2008) compared the effects of heavy load (80% 1-RM) machine squat jump training compared with individual PMax loads (20-43.5% 1-RM) on sprint performances, finding similar improvements in 10m and 30m sprint times across groups, although the heavy load group did demonstrate a greater increase in 1-RM hack squat strength (15 ± 9 %) compared to the PMax group (11 ± 8 %). It should be noted, however, that the squat jump only account for ~20% of the volume of training. Numerous authors have previously presented such velocity specific adaptations of training across a spectrum of loads (Kaneko et al., 1983; Moss et al., 1997; Jones et al., 2001; McBride et al., 2002).

It would appear, therefore, that the initial focus of athletic development should be on maximising strength, while developing appropriate technique during power exercises (ballistic and Olympic style lifts) until athletes can be considered as being strong (parallel depth back squat ≥1.9 x body mass) (Cormie et al., 2010b; Cormie et al., 2010a; Cormie et al., 2011b; Cormie et al., 2011a). Low load ballistic exercises such as squat jumps are likely to be most beneficial in developing speed-strength and power, where as higher load ballistic exercises, such as speed deadlifts, with 20-40% load from chains, are likely to develop strength-speed, once athletes have developed a base level of strength (Swinton et al., 2011b). It is important, however, that strength is maintained if such an approach is adopted, as any decline in force production would result in a decrease in power generating capacity (Cormie et al., 2011b; Haff and Nimphius, 2012).

2.1.3 Plyometric Training

Plyometric exercises are characterised by a rapid eccentric muscle action followed immediately by a rapid concentric muscle action, thereby utilising the stretch-shortening cycle (SSC), resulting in greater force, RFD, power and therefore jump performance, when compared to a muscle contracting from an isometric condition (Cavagna et al., 1968; Komi, 2000; McGuigan et al., 2006; Hawkins et al., 2009). The stretch shorten cycle utilises both elastic energy and neurological potentiation to increase force production and RFD to enhance athletic performance (Bosco and Komi, 1979; Bosco et al., 1981; Bosco et al., 1982a; Bosco et al., 1982b; Komi, 2000).

Elastic energy is generated via the lengthening of the associated tendons (series elastic component (SEC)) and the muscle fascia (parallel elastic component (PEC)), during the eccentric phase of the activity and returned during the concentric phase (Asmussen and Bonde-Petersen, 1974a; Asmussen and Bonde-Petersen, 1974b; Komi, 2000; Wilson and Flanagan, 2008). Simultaneously, during the eccentric phase, both the change in length and the rate of change in length is detected by the muscle spindles, which result in increased potentiation of the agonist muscles and therefore increased force production, during the concentric phase, referred to as the contractile element (Cavagna et al., 1968; Bosco and Komi, 1979; Bosco et al., 1981; Bosco et al., 1982a; Bosco et al., 1982b; Bobbert et al., 1996). The relative contribution of the elastic element and the contractile element have been shown to be determined by the lengths of both components, with a longer tendon resulting in a larger contribution from the elastic component and longer muscle fascicles, resulting in a greater contribution from the contractile element (Arakawa et al., 2010). It is therefore not surprising that medial and lateral gastrocnemius fascicle length, pennation angle and Achilles tendon length have been shown to be related to jump performance (Earp et al., 2010; Earp et al., 2011; Comfort et al., 2014b).

It is worth noting that if the magnitude of stretch and therefore force is too great, the stretch applied to the tendon can result in stimulation of the golgi tendon organ (GTO) which results in reciprocal inhibition of the agonist muscle (Gabriel et al., 2006; Folland and Williams, 2007). It is important, therefore, to ensure that the intensity of the plyometric task is appropriate for the individual athletes' strength level which minimises the likelihood of stimulation of the GTO. Part of the adaptive response to strength training is a reduction in the sensitivity of the GTO (Gabriel et al., 2006; Folland and Williams, 2007) , therefore requiring a higher force prior to stimulation of the GTO and the resultant inhibition of the antagonist muscle. It is possible that this apparent reduced sensitivity of the GTO is due to the increase in tendon stiffness associated with training (Narici et al., 1996; Kubo et al., 2006; Burgess et al., 2007; Kubo et al., 2007), which in turn results in a greater force required to elicit the same magnitude of stretch to the tendon.

General recommendations for plyometric training suggest that they should be performed 2-4 x week, on non-consecutive days, with 5-10 s rest between repetitions, 2-3 mins rest between sets, for 80-100 repetitions for beginners, 100-120 repetitions at intermediate level and 120-140 repetitions for advanced level athletes (Potach and Chu, 2008). Although, if the intensity of the exercise is increased; for example progressing from a countermovement jump to a depth jump, the total volume (number of repetitions) should be reduced to accommodate the increased demands of the tasks (Potach and Chu, 2008).

Relatively low loads are usually used during plyometric tasks, with numerous studies highlighting that peak power occurs at body mass (no additional external load) during jumping tasks (Wilson et al., 1993; Dugan et al., 2004; Cormie et al., 2007a; Cormie et al., 2007c; Cormie et al., 2007e; Cormie et al., 2008; Bevan et al., 2010; McBride et al., 2011; Swinton et al., 2012; Turner et al., 2012). While additional external load can be used to increase intensity of an exercise, simply performing the eccentric phase of a plyometric task more rapidly results in an increase in force required to decelerate the body, and increases the rate of lengthening of the muscles which results in greater potentiation, via stimulation of the muscle spindle (Bosco and Komi, 1979; Bosco et al., 1981; Bosco et al., 1982a; Bosco et al., 1982b; Bobbert et al., 1996). It is important to note that increasing drop height, during depth jumps, results in an increase in loading (force on ground contact) but that this also increases ground contact time.

Lower body plyometrics are commonly divided into long contact times (>250 ms), whereby large angular displacement of the ankles, knees and hips occur, and short contact times (≤250 ms) with reduced angular displacement of the associated joints (Schmidtbleicher, 1992; Wilson and Flanagan, 2008). These different categories of plyometrics are usually selected in an attempt to meet the demands of different sporting tasks, for example the longer ground contact times during the initial acceleration phase of a sprint and the low ground contact times during maximal velocity sprinting (Brughelli et al., 2011; Cross et al., 2014).

The improvements in athletic performance occur as a result of neurological adaptations, including increased neural drive, rate of neural activation and inter-muscular co-ordination which result in an increase in RFD (Chimera et al., 2004). Adaptations in muscle and tendon architecture have also been shown to enhance RFD and jump performance (Burgess et al., 2007; Vissing et al., 2008; Wilson and Flanagan, 2008), although such adaptations are likely to take longer to occur. These adaptations manifest via an increase in force development and a decrease in duration, resulting in an increased RFD during the eccentric phase, which is likely to increase stimulation of the muscle spindle therefore increasing force, RFD and power during the concentric phase (Cormie et al., 2010c). Barr and Nolte (2014) also reported that maximal squat strength is strongly associated with depth jump performances, further highlighting the need to develop force production capabilities. This is likely a product of increased force production from the relevant musculature combined with increased elastic energy return from stiffer tendons (Kubo et al., 2006; Burgess et al., 2007; Kubo et al., 2007).

Numerous studies have identified that plyometric training enhances performance in athletic tasks (Adams et al., 1992; Lyttle et al., 1996; Fatouros et al., 2000; Tricoli et al., 2005; Arabatzi et al., 2010; Lloyd et al., 2012) albeit generally in low load tasks such a vertical jump performance (Adams et al., 1992; Wilson et al., 1993; Tricoli et al., 2005). Adams et al. (1992) investigated the effect of 6 weeks of plyometric training, strength training (squats) and combined plyometric and strength training, on jump performance, in 48 recreationally trained college students. Results demonstrated that each group improved their vertical jump performance (3.30 cm, 3.81 cm, 10.76 cm respectively), although the combined training was more effective, demonstrating a significantly ($p<0.001$) greater increase in jump performance compared to the other groups. More recently, Fatouros et al. (2000) found similar results after a 12 week training programme, with each intervention resulting in an increase in jump performance (plyometric training, 6.0 cm; strength training, 5.4 cm; combined training, 9.6 cm) with a significantly ($p<0.05$) greater increase in jump performance in the combined training group. The greater increase in the combined training group is likely a result of the greater increase in maximal strength, as identified by 1-RM back squat performance in the combined group (plyometric, 6.4 kg; strength, 28.9 kg; combined, 36.1 kg), combined with the specificity of the movement patterns from the plyometric training.

In contrast to the aforementioned studies, Lyttle et al. (1996) previously reported significant ($p<0.05$) increases in jump and 1-RM back squat performance, when recreational athletes. Subjects performed 8 weeks of either power training, using the load that resulted in the greatest mean mechanical power, during SSC activities (SJ 7.1 cm, CMJ 3.6 cm, 14.0 kg), or combined power and strength training (SJ 6.7 cm, CMJ 5.6 cm, 15.0 kg), although there were no significant ($p>0.05$) differences between groups. It is worth noting, however, that the optimal load for the power training was based on inverse dynamics calculations, which has been shown to misrepresent the true power applied to the system centre of mass and therefore results in an increase in the load which elicits the greatest peak and mean power (Cormie et al., 2007a; Cormie et al., 2007c; Cormie et al., 2007b; Cormie et al., 2007d; Cormie et al., 2007e; Cormie et al., 2008; McBride et al., 2011; Lake et al., 2012) (See Chapter 3.1 for a detailed discussion of methods of assessing power). In addition, the strength training was sub-optimal, using loads which permitted 6-10 repetitions, rather than the usual high loads (85-95% of one repetition maximum (1-RM)), for 2-6 repetitions (Baechle et al., 2008), which may have reduced the resultant adaptive responses.

Similarly, Arabatzi et al. (2010) compared the effects of plyometric training, weightlifting and combined training on jump performance, in 36 college students. Results revealed significant ($p<0.05$) improvements in SJ (5.7 cm, 4.2 cm, 4.3 cm, respectively) and CMJ (5.2 cm, 4.6 cm, 5.2 cm, respectively) performance in each group, although there were no differences in improvements between groups. The importance of increasing force development capacity via focussed strength training, along with plyometric training is highlighted by the fact that when plyometrics are combined with strength training the increases in jump performance appear to be greater than either intervention alone (Adams et al., 1992; Fatouros et al., 2000), whereas combining plyometrics and weightlifting exercises does not appear to provide an additive benefit (Arabatzi et al., 2010). These differences may be attributable to the greater increases in force production during the strength training compared to the changes in force production associated with plyometric training and strength training. It also appears that most of the adaptations in countermovement jump (CMJ) performances occur during the eccentric phase, where athletes are able to perform this phase in a shorter time period and cope with the associated increase in loading via increased force production and RFD (Cormie et al., 2010a; Earp et al., 2011).

While plyometric training and combined plyometric and strength training has been shown to enhance performance (Adams et al., 1992; Fatouros et al., 2000; Harris et al., 2008), it is important to note that the greatest benefits appear to be related to increased force production (Cormie et al., 2010b; Cormie et al., 2010a; Cormie et al., 2010c; Cormie et al., 2011b). Strength has been shown to be more trainable than velocity (Cronin et al., 2002; Cormie et al., 2010a; Cormie et al., 2010c; Barr and Nolte, 2014) until athletes are strong (Squat ≥1.9 x body mass), at which time a greater emphasis should be placed on the development of velocity and power, while maintaining strength (Cormie et al., 2010b; Cormie et al., 2010a; Cormie et al., 2010c; Haff and Nimphius, 2012), in a periodised manner.

2.1.4 Olympic Lifts

Olympic lifts consist of the snatch and the clean and jerk, with Strength and Conditioning Coaches incorporating numerous variations of these exercises into their athletes' training programmes. Variations of the Olympic lifts are usually performed with the intent to move as rapidly as possible for 4-8 sets of 1-6 repetitions at loads of 75-90% 1-RM (Baechle et al., 2008).

In competition, the snatch and clean are performed with the athlete catching the bar in a full depth squat. In contrast, in training the power snatch and power clean are commonly used as substitutes, where the athlete catches the bar in a quarter squat positions; or alternatively can be caught in a split stance. Further variations of the lifts can be seen in the starting position of the lift, for example power cleans can begin with the barbell on the floor (as in competitive lifting), in the hang position (from just above the patella, with the athlete in what represents the mid-point of a Romanian deadlift, with the shoulders in front of the bar), or from mid-thigh (bar resting mid-thigh while the athlete is in a semi-squatting position, with the shoulders directly above the bar). Similar start positions can be used for the snatch and power snatch, albeit with the bar slightly higher during the hang position (the bar starts at approximately mid-thigh) and the snatch from the hip (this replaces the mid-thigh position, although the participant is still in a semi-squatting position with the shoulders directly above the bar) due to the wider grip width.

Variations of these Olympic lifts are commonly used to enhance power development during sports-specific movements (rapid extension of ankles, knees and hips) (Stone, 1993; Stone et al., 2003a; Stone et al., 2003b; Stone et al., 2007) with performance in such lifts positively associated with performance in athletic tasks, including sprint, jump and agility performances (Stone et al., 2003b; Hori et al., 2008; McGuigan and Winchester, 2008; McGuigan et al., 2010). The positive associations between such performances are unsurprising as Canavan et al. (1996) previously reported similar kinetics between Olympic style lifts (hang snatch) and squat jump performances, similar to the previous observations between the second pull phase of the snatch and jump performances by Garhammer and Gregor (1992).

Olympic lifts and their derivatives are sometimes perceived as being difficult and time consuming to perfect and incorrectly associated with a high injury risk (Faigenbaum and Palakowski, 1999); with Swedish Weightlifters reporting an incidence of knee and low back pain comparable to the general population (Chiu and Schilling, 2005). Observations of elite weightlifters have shown a range of demanding technique issues associated with each movement (Garhammer, 1979; Garhammer, 1982; Gourgoulis et al., 2000; Gourgoulis et al., 2002). However, provision of verbal and video feedback across 12 training sessions, in

Lacrosse players has been shown to substantially improve technique in the power clean (Winchester et al., 2005), highlighting the importance of appropriate coaching of these complex activities.

Attributing chronic soft tissue injuries to a specific exercise is difficult due to the other training stresses resulting in a range of confounding variables occurring concurrently, although it has been concluded that the benefits of such exercises outweigh the possible risk of injury (Stone et al., 1994; Hedrick and Wada, 2008). Although, minor soft tissue injuries to the wrists, shoulders, back, hips, knees and ankles are relatively common among individuals who perform the Olympic lifts (Konig and Biener, 1990; Hedrick and Wada, 2008). A recent report by Myer et al (2009) revealed that children had a lower risk of resistance training muscle and joint strains and sprains than adults, concluding that with appropriate instruction resistance training is safe even in children. The majority of sporting injuries are reported to occur during competition, rather than training for the sports (Maffulli et al., 1994; Maffulli et al., 2005). In the United Kingdom soccer has the highest incidence of injuries, with a higher level of competition being associated with a higher incidence of injury (Maffulli et al., 2005). In addition studies have demonstrated that supervised resistance training programmes can decrease the incidence of injury during both training and competition in their sport (Cahill and Griffith, 1978; Cahill et al., 1984; Abernethy and Bleakley, 2007; Faigenbaum and Myer, 2010), with similar findings reported in military recruits (Hoffman et al., 1999). Moreover a recently published meta-analysis revealed that interventions that increase muscle strength are the most favourable in reducing sports injuries; with the review highlighting that strength training can reduce sports injuries by approximately 30% and overuse injuries by approximately 50% (Lauersen et al., 2013).

Technical models for the 'ideal' performance in Olympic lifts has been determined by observation of elite lifters (Hakkinen et al., 1984; Gourgoulis et al., 2000; Gourgoulis et al., 2002; Chiu et al., 2010; Hadi et al., 2012; Harbili, 2012) and then applied as technical models (Pierce, 1999; Hedrick, 2004) for derivatives of these exercises for non-weightlifters (Graham, 2002; Duba et al., 2009). Such approaches, however, have been criticised as they assume that success is closely related to technique and general ignore other athletic characteristics (Lees, 2002). It is unreasonable to expect athletes from other sports to have the technique and athletic ability to perform the Olympic lifts with similar technique as Olympic weightlifters who specialise solely in these disciplines, unless they have been subject to an effective and progressive long term athlete development programme from a developmental age (Lloyd et al., 2013). In addition, athletes other than Olympic weightlifters tend to perform the power clean, power snatch and their derivatives rather than the full lifts, with technical models commonly provided to guide strength and conditioning coaches (Graham, 2002; Blackwood, 2004; Duba et al., 2009). It is important to note that the concentric phase of the power clean and clean should demonstrate the same kinematics and kinetics, with only the depth of the catch position being different between the two variations.

During Olympic lifting competitions, it has been identified that peak bar velocity (calculated from displacement time data) and peak power (calculated from system mass and acceleration of the bar) occurs during the second pull (from mid-thigh until the end of the triple extension) phase of the clean (Garhammer, 1979; Garhammer, 1980; Garhammer, 1982; Garhammer, 1985; Garhammer, 1991; Pennington et al., 2010). More recently similar findings have been observed in competitive weightlifters using both two and three-dimensional motional capture to analyse the Snatch (Isaka et al., 1996; Gourgoulis et al., 2000; Gourgoulis et al., 2002;

Pennington et al., 2010; Hadi et al., 2012; Harbili, 2012), where power was assessed using the same methods as Garhammer (1980, 1985, 1993).

Only four studies have previously reported kinetic variables during the different phases of the power clean, finding that the greatest peak force occurred during the second pull, compared to the first pull and transition phases (Enoka, 1979; Hakkinen et al., 1984; Garhammer and Gregor, 1992; Souza et al., 2002). No research however, has compared the kinetics of the different variations (mid-thigh clean pull, mid-thigh power clean, hang power clean, power clean) of the power clean to determine if the second pull phase results in the greatest peak force, peak RFD or peak power output, or if this is a product of the bar already gaining momentum during the first pull and transition phase of the power clean. No research, however, has compared the peak force or peak RFD, during the power clean, hang power clean (bar held, in the start position, just above the patella) the mid-thigh power clean and the mid-thigh clean pull (this is the concentric phase of the mid-thigh power clean without the catch phase). Furthermore, no studies have compared peak power during the power clean, hang power clean and mid-thigh power clean to establish which generates the greatest power.

Variations of the power clean are regularly incorporated in athletes' training regimes, with specific potential benefits hypothesised for each variation of the clean, although many of these theoretical benefits have not been substantiated by empirical evidence. The optimal loads which elicit peak power output during the power clean (Cormie et al., 2007c; Cormie et al., 2007b; Cormie et al., 2007e), hang power clean (Kawamori et al., 2005; Kilduff et al., 2007) and mid-thigh power clean (Kawamori et al., 2006) have been reported between 60-80% one repetition maximum (1-RM) power clean, although these were generally not significantly different at loads ±10% of the optimal load.

2.2 Areas for Further Research

As the second pull phase of the Olympic lifts has been observed to result in the greatest force (Enoka, 1979; Hakkinen et al., 1984; Garhammer and Gregor, 1992; Souza et al., 2002), bar velocity and power (Garhammer, 1979; Garhammer, 1980; Garhammer, 1982; Garhammer, 1985) and the fact that strength and conditioning coaches regularly use various derivatives of the clean (e.g. power clean, hang power clean, mid-thigh power clean and mid-thigh clean pull) it would be useful to identify differences in force time characteristics between each of these variations. The results of such findings would permit strength and conditioning coaches to make more informed decisions regarding exercise selection.

The majority of previous research has been conducted using well trained team sport athletes or Olympic Weightlifters (Haff et al., 1997; Haff et al., 2005; Kawamori et al., 2005; Kawamori et al., 2006; Cormie et al., 2007c; Cormie et al., 2007b; Cormie et al., 2007e; Haff et al., 2008), and therefore the application of these findings to inexperienced athletes is problematic. Based on the findings of previous research, where lower relative loads resulted in greater peak power, due to an increased movement velocity (Kawamori et al., 2006; Cormie et al., 2007c; Cormie et al., 2007e; Hori et al., 2007), the effect of loading on kinetic variables should be investigated, both within and between variations of the exercise. An additional area requiring further investigation is the identification of the optimal load during the power clean in relatively inexperienced collegiate athletes, as previous research has focussed on well trained athletes (Haff et al., 1997; Haff et al., 2005; Kawamori et al., 2005; Kawamori et al., 2006; Cormie et al., 2007c; Cormie et al., 2007b; Cormie et al., 2007e; Haff et al., 2008).

Finally, determining the effect of loading, on force time characteristics, during the pulling derivatives (e.g. MTCP) is of interest as they are simple exercises to learn and do not require a catch phase. The catch phase can be problematic in injured athletes and athletes that struggle to disassociate movements, especially when rapidly changing from the concentric phase of the pull to the rapid eccentric phase of the descent into the catch phase. Additionally, as pulling derivatives omit the catch phase, it is possible to use loads that are greater than 100% of the 1-RM power clean which may be beneficial in training the force end of the force velocity curve.

CRITICAL REVIEW OF LITERATURE

3 CRITICAL REVIEW OF LITERATURE

3.1 Methodological Issues with Assessment of Power

Power is expressed as the product of the force applied to and the resulting velocity of an object of interest (Winter, 2009). Therefore, knowledge of both the force applied to and the resulting velocity of the object (usually the barbell, centre of mass (COM) or system COM) are required to calculate the power applied to the object in question, (Cormie et al., 2007a; Cormie et al., 2007c; Cormie et al., 2007b; Hori et al., 2007; McBride et al., 2011; Lake et al., 2012). Assessment of velocity of either the bar, COM or system COM during squats, squat jumps and the power clean only provides a valid assessment of the power applied to the point where velocity is assessed (Cormie et al., 2007c; Cormie et al., 2007b; Hori et al., 2007; McBride et al., 2011), with Lake et al. (2012) reporting that a difference in velocity >18% can occur depending on whether velocity of the bar, COM or system COM assessed. With the study by Lake et al. (2012) using back squats, it is realistic to assume that the differences in velocity of the bar, COM and system COM would be greater in the Olympic lifts and their derivatives as the bar starts lower than the COM and usually finishes above the COM, resulting in a much greater difference between velocity of the bar, COM and system COM. Such differences in velocity are also presented in the findings of Cormie et al. (2007c). Theoretical errors underpinning the choice of instruments and the subsequent calculations for either the force or velocity component have been shown to alter the power output and the load which elicits peak power output with resultant under or over estimation of force unless measured via a force platform (Dugan et al., 2004; Cormie et al., 2007a; Cormie et al., 2007c; Cormie et al., 2007b; Hori et al., 2007; McBride et al., 2011; Lake et al., 2012).

Numerous researchers have investigated the different methods available for assessing power output during dynamic multi-joint exercises including the squat jump and power clean (Cormie et al., 2007a; Cormie et al., 2007c; Cormie et al., 2007b; Hori et al., 2007; Li et al., 2008; McBride et al., 2011; Lake et al., 2012). Three categories of methods are available to determine power during the power clean: kinetic methods, kinematic methods, and combined kinetic and kinematic methods, although a variety of combinations of these methods have been employed within the literature (Dugan et al., 2004; Cormie et al., 2007a; Cormie et al., 2007c; Cormie et al., 2007b; Hori et al., 2007; Li et al., 2008; McBride et al., 2011; Lake et al., 2012). Power estimation methods belonging to each category, including both the choice of instrument(s) and subsequent calculations, have been previously described within the literature (Cormie et al., 2007a; Cormie et al., 2007c; Cormie et al., 2007b; Hori et al., 2007; Li et al., 2008; Hansen et al., 2011; McBride et al., 2011; Lake et al., 2012). Despite several attempts, however, no standardized method for determining the power has been accepted (Dugan et al., 2004; Cormie et al., 2007a; Cormie et al., 2007c; Cormie et al., 2007b; Hori et al., 2007; Li et al., 2008; Hansen et al., 2011; McBride et al., 2011; Lake et al., 2012). Although, Lake et al. (2012) suggest that inverse dynamics based on barbell velocity should be avoided during lower body exercises. In general, the different methods either result in calculation of the power applied to the object (usually the barbell), COM or system COM, but result in differing power values and intensities which elicit peak power.

3.1.1 Kinetic methods

The most common method for assessing power output during Olympic lifts and their derivatives is by numerically integrating ground reaction force time data, obtained from performing the exercise with the athlete standing on a force platform, usually referred to as either a forward dynamics approach (Cormie et al., 2007a; Cormie et al., 2007c; Cormie et al., 2007b; Hori et al., 2007) or an impulse-momentum approach (Dugan et al., 2004). Within the numerical integration method, force applied to the system (body + external load) COM (F) is directly collected; therefore it is important that the full system mass is applied to the force platform prior to the onset of movement (Hori et al., 2007; McBride et al., 2011). System COM velocity (v) is obtained by time (t) integration (most commonly by applying the Simpson or trapezoidal rule (Street et al., 2001) of system COM acceleration (a); that is, F minus system weight (W) divided by system mass (m) (Cavagna, 1975; Driss et al., 2001):

$$v = \int_0^t a\,\mathrm{dt} = \int_0^t \frac{(\mathrm{F} - \mathrm{W})}{\mathrm{m}}\,\mathrm{dt} \tag{1}$$

For each time point (i), power (P) is calculated as the product of F and v:

$$\mathrm{P}_{(i)} = \mathrm{F}_{(i)} * v_{(i)} \tag{2}$$

Peak power output is identified as the greatest power output at any given time point during the concentric phase of the activity, with mean power output defined as the average of the power outputs at each individual time point during the concentric phase (based on sampling frequency) divided by the number of time points within the movement duration.

As the focus of the Olympic lifts, and their derivatives, is to maximize vertical displacement of the system COM it is suggested that this should be calculated exclusively via vertical ground reaction forces (Cormie et al., 2007a; Cormie et al., 2007c; Cormie et al., 2007b; Hori et al., 2007; McBride et al., 2011). As the motion of the barbell does not necessarily represent motion of the system COM (Hori et al., 2007; Li et al., 2008; Hansen et al., 2011; McBride et al., 2011; Lake et al., 2012), while the effect of horizontal motion of the barbell on the system COM remains unclear. It is worth acknowledging, that in Olympic weightlifters bar displacement and velocity may be important than the system COM, whereas for athletes performing such lifts to enhance lower body power output the motion of the bar is less important, with maximising power applied to the system COM the primary focus, in line with previous recommendations by McBride et al. (2011) and Lake et al. (2012).

The accuracy of the numerical integration method is limited only by the precision of the measured forces and the precision of the initial velocity integration constant (Cavagna, 1975; Maus et al., 2011). A correctly mounted and calibrated force platform (Lees and Lake, 2008) sampling at a sufficient frequency (1000 Hz recommend, although ≥200 Hz has been shown to be sufficient (Vanrenterghem et al., 2001; Hori et al., 2009)) is considered the gold standard of force measurement during ground based tasks. Errors related to the precision of the measured forces, such as instrumental instability and background noise, appear to be minimal. The precision of the initial velocity integration constant and the determination of system mass are therefore the primary threats to the integrity of the numerical integration method (Cavagna, 1975; Vanrenterghem et al., 2001; Maus et al., 2011). To ensure precision and accuracy of these measures it is imperative that subjects remain stationary for a short period (~0.5 s), with the system mass applied to the force platform, prior to the commencement of any movement, the integration constant of initial velocity is a known zero upon the start of integration at the initiation of movement (Cavagna, 1975; Vanrenterghem et al., 2001; Hori et al., 2007; Hori et al., 2009; Maus et al., 2011).

The numerical integration method can accurately calculate both the force applied to the system COM and the resultant velocity of the system COM during lower body power exercises, resulting in this method being recommended as the ‘gold standard’ criterion for the calculation of power applied to the COM during lower body exercises (Cormie et al., 2007a; Cormie et al., 2007c; Cormie et al., 2007b; Li et al., 2008; Lake et al., 2012). It should be acknowledged, however, that power may be underestimated as the COM moves independently of the bar which may result in underestimation of velocity and therefore power, calculating power of system COM avoids this (Haff et al., 1997; Cormie et al., 2007c; Lake et al., 2012).

3.1.2 Kinematic methods

Motion analysis using video or linear position transducers (LPT) can be utilized to obtain the velocity of the barbell from displacement time data. During the Olympic lifts it is essential to note that this does not represent the velocity of the COM or system COM as they move independently of each other (Garhammer, 1993; Cormie et al., 2007c; McBride et al., 2011; Lake et al., 2012). Using this approach (inverse dynamics), barbell velocity (*v*) and acceleration (*a*) are obtained at each time point (i) by differentiation (most commonly finite difference technique) of the barbell displacement (x) time (t) data (Cormie et al., 2007c; Winter, 2009):

$$v_{(i)} = \frac{dx}{dt} \tag{3}$$

$$a_{(i)} = \frac{dx^2}{dt^2} \tag{4}$$

The force applied to the system COM (F) is obtained as the product of system mass (m) and the summation of system COM acceleration (based on acceleration of the barbell) and acceleration due to gravity (g) (Newton's second Law):

$$F_{(i)} = m * (a_{(i)} g) \tag{5}$$

Power is then calculated through equation 2.

This method, often referred to as the inverse dynamics method (Cormie et al., 2007a; Cormie et al., 2007b; Hori et al., 2007), has been applied to data obtained from video (Garhammer, 1980; Garhammer, 1982; Garhammer, 1991; Lake et al., 2010), motion analysis systems (Gourgoulis et al., 2000; Gourgoulis et al., 2002; Chiu et al., 2010; Chiu, 2010a) and linear position transducers (Cormie et al., 2007a; Cormie et al., 2007c; Cormie et al., 2007b; Hori et al., 2007; Hansen et al., 2011) during lower body power exercises.

Similar to the numerical integration method, the LPT method calculates power along the vertical axis only (Dugan et al., 2004; Cormie et al., 2007a; Cormie et al., 2007c; Hori et al., 2007). Therefore, the validity of the LPT method is based on the assumption that the attachment point does not undergo any extraneous horizontal motion as this appears to artificially inflate the vertical displacement value, consequently overestimating both the velocity and power outputs (Cormie et al., 2007a; Cormie et al., 2007c). In addition, calculated power is also elevated due to the over-estimation of force via the calculations of force from system mass, based on velocity and therefore acceleration of the barbell (Equation 5), whereas if barbell mass alone is used in place of system mass force and therefore power are underestimated (Hori et al., 2007) as it is the mass of the entire system which is accelerated during such triple extension movements. To allow vertical only displacement to be accurately measured, horizontal motion may be corrected for using basic trigonometry with the application of two triangulated LPT (Cormie et al., 2007a; Cormie et al., 2007c). Moreover, only horizontal motion of the barbell has been considered, while asymmetrical movement of the bar and deformation of the barbell itself may influence the resultant power values (Chiu et al., 2008; Chiu, 2010a; Chiu, 2010b), with Lake et al. (2010) demonstrating a 4-6% difference in peak power from assessing bar velocity at either end of the bar across a range of loads.

When assessing Olympic Weightlifting performance in a competitions setting, however, it is worth noting that it is only possible to assess bar velocity from two dimensional video analyses, as performed by Garhammer (1979, 1980, 1982, 1991). What must be considered here is the effect of sampling frequency on the calculation of barbell velocity and its resultant affect on the calculation of peak power, with the aforementioned studies using 25 and 50 frames per second. Similarly, sampling frequency of LPT systems should also be taken into account when comparing results of studies, or between technologies (Cronin et al., 2004; Hori et al., 2007; Harris et al., 2010a). It is essential to identify how such methods compare to alternative laboratory based methods of assessing power output, as numerous authors have investigated (Cormie et al., 2007a; Cormie et al., 2007c; Hori et al., 2007; Li et al., 2008; McBride et al., 2011; Lake et al., 2012), as this permits appropriate comparisons between methods.

3.1.3 Comparisons of Different and Combined Methods

Hori et al. (2007) compared four different methods of assessing power during the hang power clean and squat jump in trained males: one LPT plus barbell mass, one LPT plus system mass, FP only and FP plus LPT. Results demonstrated that the LPT plus barbell mass significantly ($p<0.05$) underestimate force, due to the exclusion of body mass, and therefore power (1644 ± 295 W) (>40% lower than inverse dynamics approach) compared to each of the other methods (FP = 3079 ± 638 W; LPT plus system mass = 3821 ± 917 W; FP plus LPT = 4017 ± 833 W). The authors also concluded that calculating power using the FP and inverse dynamics was the most reliable method for both the hang power clean (ICC r = 0.90) and squat jump (ICC r = 0.97). The assumption that the change in bar velocity (acceleration) represents the change in velocity (acceleration) of the centre of mass (COM) needs to be treated with caution, as there were significant differences ($p<0.05$) in barbell velocity and velocity of COM calculated from the LPT ($2.16 \pm 0.25\ m \cdot s^{-1}$) and FP ($1.48 \pm 0.20\ m \cdot s^{-1}$), respectively, demonstrating that inverse dynamics is likely to overestimate the force applied to the system. Similar findings for velocity and the therefore power applied the barbell, COM and system COM have been reported by McBride et al. (2011) and Lake et al. (2012).

Cormie et al. (2007c) progressed from the previous study and compared six different methods of assessing power during squats, squat jumps and power cleans across a spectrum of loads: one LPT (including barbell mass), one LTP (including system mass), two LPT's, FP only, FP plus one LPT and a FP plus two LPT's, in well trained males. Results demonstrated that one LPT plus barbell mass under-valued force and therefore power during the squat and jump squat, where as the one LPT and two LPT methods (including system mass) over-valued force (due to the acceleration of the barbell being greater than the acceleration of the system COM), and therefore power in line with the findings of Hori et al. (2007). The differences in the peak power outputs calculated via the different methods are illustrated by the optimal load for power output occurring at different loads across methods. During the power clean, the kinematic only data (1 LPT and 2 LPT), which excluded body mass, under-valued force resulting in identification of an optimal load for peak power at 30% 1-RM, whereas the methods using kinetic data (FP, FP plus 1 LPT and FP plus 2 LPT) identified optimal load as 80% 1-RM, although peak power values differed across all methods. The combined methods, using both FP and LPT data resulted in greater power outputs, compared to the FP only method, due to the greater velocity associated with the barbell, compared to the velocity of the system COM (McBride et al., 2011; Lake et al., 2012).The authors caution that calculating velocity from force time data tends to undervalue bar velocity and therefore result in lower power outputs (Cormie et al., 2007c), however, this is power applied to the barbell and not power applied to the system COM. In contrast, Lake et al. (2012) caution the use of barbell velocity when calculating power as it was shown to be >18% higher than velocity of system COM, which results in greater acceleration values required to approximate force. For most athletes power applied to the system is more important than power applied to the bar, however, for Olympic lifters barbell displacement, velocity and power is highly important.

An additional study by Cormie et al. (2007b) investigating the influence of the addition of body mass, body mass minus shank and foot mass on power output during the squat, squat jump and power clean demonstrated that the exclusion of body mass results in a significant decrease ($p<0.05$) in power output and the load power relationship. Further supporting previous findings that body mass should be included in the calculation to ensure that force is not under-estimated and that methods of assessing power, during such exercises, should be standardised to ensure that findings are comparable (Cormie et al., 2007c; Hori et al., 2007).

More recently, McBride et al. (2011) compared the effects of calculating power from velocity of the bar, body COM or system COM, across a range of loads for the squat, squat jump (0-90% 1-RM) and power clean (30-90% 1-RM) at 10% increments. Results revealed that the load that elicits peak power varies during the squat when calculated from velocity of the bar (90% 1-RM), body (10% 1-RM) or system (50% 1-RM), with a similarly diverse range of loads for the squat jump (80%, 0%, 0% 1-RM respectively). Interestingly, the authors found minimal difference in the load that elicits peak power during the clean, when calculated from velocity of the bar (90% 1-RM), body (90% 1-RM) or system (80% 1-RM), although there were dramatic differences in velocities and peak power outputs across methods bar (1.78 ± 0.12 $m\cdot s^{-1}$; 2145 ± 407 W) body (0.81 ± 0.18 $m\cdot s^{-1}$; 1125 ± 528 W) system (0.73 ± 0.15 $m\cdot s^{-1}$; 1611 ± 505 W). These results reinforce the fact that the change in bar velocity does not represents the change in velocity of the centre of mass (COM) as previously noted by Hori et al. (2007). It is worth noting that the low peak power values reported by McBride et al. (2011) are as a result of the fact that system mass was not used in the calculation of force, which has previously been reported to result in an underestimation of force and therefore power (Cormie et al., 2007c; Hori et al., 2007).

During the power clean and its derivatives, power applied to the system should be assessed to monitor training adaptations, rather than power applied to the bar, which could result from improved technique in the exercise, it is recommended that kinetic data should be collected via a FP and calculated via forward dynamics (Cormie et al., 2007a; Cormie et al., 2007c; Cormie et al., 2007b; Hori et al., 2007; McBride et al., 2011). Similar conclusions regarding the assessment of power during the squat jump have also been suggested (Hansen et al., 2011; McBride et al., 2011; Lake et al., 2012) with McBride et al (2011) suggesting that assessing power applied to the bar may be more meaningful for weightlifters and throwing athletes, whereas assessment of power applied to the system COM may be more meaningful in jumpers and sprinters. Therefore, if monitoring changes in lower body power output, or the making kinetic comparisons of exercises or variations in loading, a forward dynamics approach should be used when assessing power. In contrast, if assessing changes in technique or performance in weightlifters, bar displacement and velocity, with the calculation of power output using inverse dynamics may be more valid and informative to the coach and athlete.

Due to the variations and limitations in each of the aforementioned kinetic, kinematic and combined methods of assessing power, during lower body exercises it has been suggested that the methods should be standardised to ensure that they are comparable (Cormie et al., 2007c; Hori et al., 2007; McBride et al., 2011; Lake et al., 2012). The concern with methodologies that use barbell displacement time data (LPT or video) is the necessity for extensive data manipulation. An inverse dynamics approach is required to determine force from displacement data and although these calculations are based on sound mathematical principles, the methodologies are restricted through the collection of kinematic data, including the calculation of force based on the acceleration of the barbell rather than the system COM. The amplification of noise and the associated possibility of compromising the integrity of the derived data set are inherent in such manipulations (Wood, 1982). These methodologies rely on double differentiation procedures involving different filtering and smoothing operations, which increase the potential for error, and therefore affects the validity of the derived power values (Dugan et al., 2004; Cormie et al., 2007c).

An additional disadvantage associated with methods relying solely on kinematic data is the inability to account for the movement of the COM that occurs independently of the barbell, an important factor in weightlifting movements (Garhammer, 1993). Displacement based systems track only barbell displacement, resulting in calculation of velocity and acceleration of the barbell, which is greater than that of the system COM (Cormie et al., 2007c; Hori et al., 2007). As a consequence, the force–time curve during the power clean is determined independent of the action of the body that is producing the force acting on the barbell. Thus the resulting force and power calculations are representative of the barbell and not the entire system; this contributes to the elevated power values observed in the power clean (Cormie et al., 2007c; Hori et al., 2007). These factors may explain the overestimation of power output with kinematic methods, although, in terms of success in weightlifting, power applied to the bar may be the most important and valid method of assessment.

3.1.4 Summary

For the assessment and monitoring of athletic development in athletes, other than Olympic weightlifters, it is suggested that kinetic methods of assessing power are used, with the full system mass applied to the force plate prior to initiation of the movement, as this represents the power of the system as a whole. In addition, this would make power outputs during different exercises comparable, such as comparisons between the power clean and squat jump, where using barbell velocity varies dramatically between exercises. In contrast, for Olympic weightlifters power applied to the barbell and barbell displacement is more important in order to ensure a successful lift in training and competition.

3.2 Rate of Force Development

3.2.1 Force and Rate of Force Development

As the term suggests, RFD refers to the amount of force generated in a given time period, usually identified as maximum or peak RFD during a task, or muscle action, or the mean RFD achieved in a specified time-epoch. Rate of force development can be calculated as the slope of the force time curve (Δforce/Δtime), although numerous variations in methods have been used; for example peak RFD calculated as the maximal tangential slope between two adjacent data points during an activity, or mean RFD as the slope of the force time curve over a specific time epoch, 0-50 or 0-250 ms (Discussed in detail in section 3.2.5).

In sporting environments, RFD may be more important than peak force, as force needs to be developed rapidly, due to the short periods of time (50-250 ms), such as ground contact times, in which the athlete has to develop the greatest force possible (Tidow, 1990; Andersen and Aagaard, 2006). For example, during high speed sprinting and running ground contact times <250ms have been reported (Tidow, 1990; Weyand et al., 2000; Wright and Weyand, 2001; Weyand et al., 2010), with the ability to generate high ground reaction forces, in <200 ms, rather than leg speed being identified as the key determinant of running velocity (Weyand et al., 2000; Weyand et al., 2010). During sprinting, contact times >200 ms (222 ± 18 ms) have been observed during the initial acceleration phase, reducing to 169 ± 7.9 ms during the maximal velocity phase (Cross et al., 2014), although Brughelli et al. (2011) previously reported longer contact times, of 209.7 ± 19.7 ms, during maximal velocity sprinting in amateur Australian rules football players. Although there is some variation across this data, contact times are still <250 ms, highlighting the importance of developing the ability to apply high forces in a short time period. In contrast, longer durations >300 ms are required for maximal force development (Thorstensson et al., 1976).

3.2.2 Factors Affecting Rate of Force Development

Physiological factors affecting RFD include cross sectional area (CSA) of the muscle (Hakkinen et al., 1985; Narici et al., 1996; Aagaard et al., 2002; Suetta et al., 2004; Folland and Williams, 2007), maximal strength (maximal force production) (Hakkinen et al., 1985; Schmidtbleicher, 1992; Narici et al., 1996; Andersen and Aagaard, 2006; Holtermann et al., 2007; Cormie et al., 2010b; Cormie et al., 2011b), muscle fibre type and composition (Harridge et al., 1996), along with neural drive (Grimby et al., 1981; Aagaard et al., 2002; Gruber and Gollhofer, 2004; Folland and Williams, 2007; Holtermann et al., 2007; Tillin et al., 2012) and visco-elastic properties of the musculo-tendinous complex (Narici et al., 1996; Bojsen-Moller et al., 2005; Burgess et al., 2007; Tillin et al., 2012).

Strong, positive association between peak force and RFD measures have been observed, as may be expected (Mirkov et al., 2004; Stone et al., 2004; McGuigan and Winchester, 2008; McGuigan et al., 2010). In addition, when Oliveira et al. (2013) investigated the effects of 6 weeks of explosive strength training on early and late phase mean RFD (10-250 ms at 10 ms intervals), they observed a significant ($p \leq 0.006$) increase in force production and mean RFD within 10 ms, but no change in RFD over longer epochs in the training group, and no changes ($p > 0.05$) in the control group. Further analysis revealed that the increase in mean RFD was attributed to the increase in maximal force production. Unfortunately, this investigation only used the knee extension exercise as a training intervention, performing 6-10 repetitions per set, and only assessed force and RFD during the same exercise; therefore making it difficult to generalise and apply these finding to ‘normal’ strength training incorporating heavy load (≥85% 1-RM), low repetition (≤6), multi-joint exercises and athletic tasks.

Training studies, over 8-24 weeks, have reported that increases in mean RFD over 150-250 ms mirror increases in maximal muscle force production (Hakkinen and Komi, 1983; Hakkinen et al., 1985; Narici et al., 1996; Aagaard et al., 2002; Andersen and Aagaard, 2006). Hakkinen and Komi (1983) investigated the changes in mechanical characteristics after 16 weeks of high intensity (80-120% MVIC) concentric and eccentric knee extension training, in 14 trained men. Results demonstrated significant ($p<0.05$) increases in force and RFD, during jump performances along with increases in isometric force production. The authors speculated that no changes occurred in the elastic properties of tendons or fascia as there was no alteration in eccentric utilisation ratio, although no assessment of tendon properties was performed. After a further 8 weeks of detraining there was a significant ($p<0.001$) decrease in peak force, but only a non-significant ($p>0.05$) decrease in RFD. Similarly, a later study by Hakkinen et al. (1985) studied the effects of 24 weeks of high intensity (70-120% MVIC; concentric and eccentric) training of the knee extensors, on force, RFD and cross sectional area (CSA), in 11 strength trained males. An increase in isometric force, RFD and CSA, occurred during the first 12 weeks, with no further changes during the final 12 weeks of training. During an additional 12 weeks of detraining, force and cross sectional area decreased, as would be expected once the training stimulus has been removed.

More recently, Aagaard et al. (2002) studied the effects of 14 weeks of heavy strength training (3-10 RM loads), using single and multi-joint machine exercises, on isometric knee extension force, mean RFD (0-30, 0-50, 0-100 and 0-200ms) and neural drive. Results demonstrated a significant ($p\leq0.01$) increase in isometric force and isometric mean RFD across all epochs and peak RFD, along with an increase in EMG amplitude and rate of rise in EMG, post training. The changes in EMG amplitude and rate of rise in EMG indicate increases in neural drive as a result of the training intervention. Similarly, Andersen and

Aagaard (2006) investigated the influence of maximal muscle strength on contractile properties and mean RFD in 25 sedentary males. The results demonstrated strong correlations ($r=0.89$, $p<0.001$) between MVC and mean RFD (200 ms), with similar relationships for mean RFD >90 ms, with MVC accounting for 52-81% of mean RFD between 90-250 ms.

The generalisation of the findings of the aforementioned studies is limited in an athletic setting, due to the training status of the subjects, their use of isometric, single joint assessment of force and RFD, which does not represent the dynamic and multi-joint nature of athletic performances. Additionally, many of the interventions use single joint exercises, with loads that are not comparable to those generally recommended for strength and power development in athletic populations (Stone et al., 2007; Baechle et al., 2008; Cormie et al., 2011b; Cormie et al., 2011a; Haff and Nimphius, 2012). Multi-joint isometric assessments, such as the isometric mid-thigh (IMTP) pull, however, may be more appropriate and have been shown to be reliable (Comfort et al., 2014a) and relate to performance in tasks such as vertical jumping (Kawamori et al., 2006; Nuzzo et al., 2008; McGuigan et al., 2010; Khamoui et al., 2011; West et al., 2011), maximal squatting (McGuigan and Winchester, 2008; McGuigan et al., 2010) and performance in the Olympic lifts (Haff et al., 2005).

3.2.3 Multi-Joint Assessment of Rate of Force Development

Isometric multi-joint assessment using either the mid-thigh pull (Haff et al., 1997; Haff et al., 2000; Stone et al., 2004; Haff et al., 2005; Kawamori et al., 2006; Haff et al., 2008; McGuigan and Winchester, 2008; Nuzzo et al., 2008; McGuigan et al., 2010; Nuzzo et al., 2010), or back squat (Wilson et al., 1995; Nuzzo et al., 2008), have been extensively used to determine the relationships with dynamic athletic tasks. Haff et al. (2005) demonstrated strong correlations between peak force and isometric peak RFD (as measured during the IMTP) and clean and jerk (r = 0.69; r = 0.69) and snatch (r = 0.93; r = 0.79) performance in competitive female weightlifters. Kawamori et al. (2006) found peak force during IMTP to be correlated with jump height in both the countermovement jump (CMJ) (r = 0.82) and squat jump (SJ) (r = 0.87), however, peak RFD was not associated with performances in the SJ and CMJ, in Olympic weightlifters.

Numerous other authors have also reported similar relationships between absolute and relative peak force during the IMTP, isometric squat and vertical jump performance (Nuzzo et al., 2008; McGuigan et al., 2010; Khamoui et al., 2011; West et al., 2011). Nuzzo et al. (2008) found stronger correlations between maximal strength assessments (1-RM back squat and 1-RM power clean) and peak force and peak power during CMJ performances (r=0.791-0.896, $p \leq 0.05$), compared to peak force during the IMTP (r=0.750, $p \leq 0.05$) and isometric squat (r=0.706, $p \leq 0.05$). In contrast, only weak and non-significant relationships were observed between IMTP, isometric squat and jump height, in collegiate male football and track and field athletes; with no meaningful or significant relationships observed between force measures and jump height. Additionally, when the data was ratio scaled (force / body mass) the relationships remained but were slightly reduced, although jump height was associated with relative 1-RM back squat (r=0.690, $p \leq 0.05$), relative power clean 1-RM, (r=0.642, $p \leq 0.05$), and IMTP relative peak force (r=0.588, $p \leq 0.05$). A moderate and significant correlation (r=0.653, $p \leq 0.05$) was also observed between mean RFD during the IMTP and peak power during CMJ performance.

In a study using well trained cyclists, Stone et al. (2004) reported that peak force and peak RFD, during the IMTP, were more closely associated with peak power output, during a modified Wingate test ($r=0.74-0.90$, $p<0.05$), compared to power output during jumping tasks. In addition they also observed that the faster cyclists generated significantly ($p<0.05$) greater peak force (4164 ± 803 N) compared to the slower cyclists (2795 ± 528 N) and greater peak RFD (13250 ± 5318 $N.s^{-1}$ vs.10326 ± 2209 $N.s^{-1}$; $p>0.05$), although this was not statistically significant.

McGuigan et al. (2008) reported strong correlations ($r = 0.61-72$, $p<0.05$) between peak force during the IMTP and 1-RM back squat and power clean performances, in well trained collegiate football players. In contrast peak RFD was not associated with performance with 1-RM or jump performances. More recently, McGuigan et al. (2010) found similar relationships between performance in the IMTP and dynamic performances, in recreationally trained men, with an almost perfect correlation ($r=0.97$, $p<0.05$) between peak force during the IMTP and 1-RM back squat performance. The authors also observed good associations between peak force, during the IMTP, and vertical jump height ($r=0.72$, $p<0.05$) and a slightly weaker association between maximal back squat performance and vertical jump height ($r=0.69$, $p<0.05$). In contrast, peak RFD did not relate well to other performance measures.

Khamoui et al. (2011) found the strongest relationships between relative peak force (peak force / body mass) during the IMTP and vertical jump height ($r=0.62$, $p<0.05$) and peak velocity during vertical jumps ($r=0.61$, $p<0.05$), in recreationally trained males. The similarity between these two correlations is not surprising as jump height was calculated from velocity of centre of mass at take off, using the impulse momentum relationship. In addition, mean RFD at 50 and 100 ms was also moderately associated with peak velocity (r=0.56, p<0.05) and acceleration of the barbell (r=0.52, p<0.05; r=0.49, p<0.05, respectively) during the high pull; although mean RFD was not associated with any of the jump or high pull data. The authors suggest that mean RFD during the initial 50-100 ms may be a better predictor of dynamic performances, and more important to develop in athletes compared to mean RFD across longer epochs. Similarly, West et al. (2011) also reported significant inverse correlations between force at 100 ms (r = -0.68) and 10 m sprint performance, but also between peak RFD (r = -0.66) and 10m sprint performance, in rugby league athletes.

In contrast, peak RFD during isometric squats, performed on a Smith machine were not associated with short sprint performance, whereas peak RFD and force at 30 ms, during a squat jump, were related (r-0.445; r-0.616) to 30 m sprint performance (Wilson et al., 1995). However, the participants in this study appeared to take approximately 1.5 s to achieve peak force, which is likely to have substantially reduced the peak RFD, as data from our laboratory demonstrates, that peak RFD during IMTP is achieved in <0.5 s. It is likely that dynamic assessment of RFD may be a better predictor of performance in athletic tasks, due to their dynamic nature, however, dynamic tasks require higher skill levels and are not as easy to standardise as isometric assessments.

It appears from the consensus of findings that absolute and relative peak force, during the IMTP, are more closely associated with dynamic performances than peak RFD (Stone et al., 2004; McGuigan and Winchester, 2008; Nuzzo et al., 2008; McGuigan et al., 2010; Khamoui et al., 2011). However, the lack of association between RFD during isometric tasks and dynamic tasks may be due to the inconsistencies in methods used to calculate RFD; for example, calculating peak RFD during a 20 ms sampling window, or the slope of the force time curve over a specific time epoch, 0-250 ms, with some studies not stating a specific method (discussed in more detail later in this chapter, section 3.2.5). In addition, RFD during the initial 50-100 ms may be more important than peak RFD in determining performance in athletic tasks (Khamoui et al., 2011; West et al., 2011). It is possible that monitoring RFD during dynamic tasks, such as the hang power clean, or during loaded jumping tasks, may be more closely associated with performance in athletic tasks, due to the dynamic nature of the activities.

3.2.4 The Role of Rate of Force Development

McLellan, Lovell & Gass (2011b) investigated the role of RFD in jump performance in well trained rugby league players, finding that peak RFD was a strong predictor (r=0.68m p<0.01) of CMJ performance and SJ performance (r=0.76, p<0.01). In contrast to most other studies, however, arm swing was permitted during the CMJ in this study, which has been shown to alter the kinetics and kinematics and increase vertical displacement during jump performance (Hara et al., 2008; Domire and Challis, 2010; Blache and Monteil, 2013; Floria and Harrison, 2013a). It is also worth noting that RFD showed the lowest reliability (ICC r = 0.89) of all kinetic variables; although this was still acceptable based on the recommendations of Cortina (1993), and Weir (2005) although the authors caution the interpretation of changes in RFD due to this observed variability. This study demonstrates that athletes with higher peak RFD tend to jump higher during both the SJ and CMJ. While it should be noted that such a correlation does not imply cause and effect it is plausible to assume that increases in peak force and peak RFD are likely to result in increases in jump performance, based on the findings of previous research (Baker and Nance, 1999; Baker, 2001; Baker et al., 2001; Stone et al., 2003a; Cormie et al., 2007d; Nuzzo et al., 2008; Cormie et al., 2010b; Cormie et al., 2010a; Cormie et al., 2011b). This is further supported by the research of Floria and Harrison (2013b) who observed that young female gymnasts with higher peak RFD scores also jumped higher during the CMJ. It is important to note, however, that RFD alone may be limited when relating this kinetic variable to performance, as an individual can produce a low force, but if produced quickly this leads to a high RFD which is unlikely to transfer to a ‘good’ athletic performance (Bellumori et al., 2011; Haff and Nimphius, 2012).

A later study by McLellan and Lovell (2012) also highlighted the importance of the assessment of peak RFD, as they observed that peak RFD and peak power during a CMJ were reduced at both 30 mins and 24 hours post rugby league match, and did not return to normal for 48 hours post match, whereas, peak force was only significantly reduced 30 mins post match. The authors concluded that assessment of peak RFD, during a CMJ, post match in rugby league may be a useful indicator of neuromuscular fatigue and readiness to train. They also observed that peak RFD and peak power assessed 30 mins and 24 hours post match correlated well ($r>0.585$, $p<0.05$) with impacts in zones 4 (7.1-8.0 G), 5 (>8.1-10.0 G) and 6 (>10 G) and total impacts during the match. In contrast an earlier study by McLellan, Lovell and Gass (2011a) showed that hormonal and endocrine markers did not return to baseline for 5 days post rugby league match, which was attributed to the impacts during the game. These apparent contradictory findings are important for the strength and conditioning coach and coach as they highlight that although the body may not fully recover from the trauma associated with high impact forces (≥8.1 G) for 5 days, neuromuscular function is restored within 48 hours. Based on these findings it would appear reasonable to suggest that between 2-5 days post game contact / impacts in training should be minimised to promote full recovery, but that during this time frame neuromuscular conditioning can take place as kinetic variables will have returned to normal. Based on these findings, assessment of peak RFD may also be a useful method of determining readiness to train, with Peñailillo et al. (2014) demonstrating that decreases in knee extensors isometric RFD (100-200 ms), is a better indicator of exercise induced muscle damage, compared to peak force during a MVIC.

Further research should identify if either multi-joint isometric (e.g. IMTP) or dynamic assessment (mid-thigh pull) of peak RFD is preferential for identification of neuromuscular fatigue.

3.2.5 Methodological Differences in Assessment of Rate of Force Development

Rate of force development is calculated as the slope of the force time curve (Δforce/Δtime), although numerous variations in methods have been used; for example calculating RFD as the steepest slope between two adjacent force samples (peak RFD), or the slope of the force time curve over a specific time epoch (mean RFD). This variation in methodologies can lead to difficulties when comparing RFD values between studies.

During single joint isometric assessments of RFD, two different methods of calculating RFD have been reported, with the peak (or maximum) RFD usually reported as the maximal tangential slope over any two adjacent samples during the initial 200 ms (Aagaard et al., 2002; Bojsen-Moller et al., 2005; Andersen and Aagaard, 2006; Gruber et al., 2007), although Oliveira et al. (2013) report maximum (peak) RFD as peak force / time to peak force which actually results in mean RFD. Inconsistencies in reporting and calculating RFD may lead to large discrepancies in the RFD values reported within the literature. There is consistency between authors, however, when reporting RFD for different time epochs, with the slope of the force time curve (change in force / time) being used to calculate mean RFD across each epoch (Table 3.1). As previously mentioned, although single joint isometric assessments of peak force, peak RFD and mean RFD are accurate and reliable they generally do not relate well to performance in athletic tasks, therefore multi-joint assessments may be preferable in athletic populations.

Table 3.1 Isometric Single Joint Assessments

Joint	Sampling Frequency	Time Period	Calculation Method	Authors
Knee (Extension)	1000 Hz	Three trials of 2 s (60 s rest)	0-30, 0-50, 0-100, 0-200 ms = mean RFD via the slope of force-time curve. Peak RFD: Maximal tangential slope over any 2 ms during the initial 200 ms	(Aagaard et al., 2002)
Knee (Extension)	1000 Hz	Four trials of 3 s (60 s rest)	0-10, 0-20, 0-30,..., 0-250 ms = mean RFD via the slope of force-time curve. Peak RFD: Maximal tangential slope over any 2 ms during the initial 200 ms	(Andersen and Aagaard, 2006)
Knee (Extension)	1000 Hz	Three trials of 2 s (60 s rest)	0-30, 0-50, 0-100, 0-200 ms = mean RFD via the slope of force-time curve. Peak RFD: Maximal tangential slope over any 2 ms during the initial 200 ms	(Bojsen-Moller et al., 2005)
Ankle (Plantar Flexion)	1000 Hz	Three trials (Duration not stated)	0-50, 50-100, 100-150, 150-200 ms Peak RFD: Maximal tangential slope over any 2 ms during the initial 200 ms	(Gruber et al., 2007)
Knee (Extension)	Not reported	Three trials of 5 s (30 s rest)	0-10, 0-20, 0-30,..., 0-250 ms = mean RFD via the slope of force-time curve. Maximum RFD = Peak force / time to peak force (Mean RFD)	(Oliveira et al., 2013)

During multi-joint isometric assessments of RFD the terms maximum RFD and peak RFD are used interchangeably, within the literature, with some authors only referring to RFD and not specifically stating if this refers to mean or peak RFD (Nuzzo et al., 2008; Cormie et al., 2010b; Cormie et al., 2010a; Khamoui et al., 2011) (Table 3.2). On two of these occasions the authors calculate mean RFD by slope of the force time curve (change in force / time (Nuzzo et al., 2008; Khamoui et al., 2011)) and on two other occasions the methods for calculating RFD during the isometric squat is not clear in the methods (Cormie et al., 2010b; Cormie et al., 2010a). When peak RFD is stated it has been calculated as the maximal tangential slope over any two adjacent samples (Table 3.2), however, the range of sampling frequencies between studies (500-1000 Hz) will affect the precision of such measures. In contrast, when specific epochs are used the calculation provided results in mean RFD, for the specific epoch, using the slope of force time curve for the allotted duration (Table 3.2)

Table 3.2 Isometric Multi-joint Assessment

Activity	Sampling Frequency	Time Period	Calculation Method	Authors
IMTP	600 Hz	Two trials 5 s (180 s rest)	Peak RFD = Maximal tangential slope over any two adjacent samples	(Comfort et al., 2014a)
Squat	1000 Hz	Three trials 3 s	RFD calculation not stated for isometric squat*	(Cormie et al., 2010a)
Squat	1000 Hz	Three trials 3 s	RFD calculation not stated for isometric squat*	(Cormie et al., 2010b)
Unilateral Leg Press	500 Hz	Three trials 3 s	Peak RFD = Maximal tangential slope over any two adjacent samples. RFD 0-30, 0-50, 0-100, 100-200 ms = mean slope of force-time curve	(Gruber and Gollhofer, 2004)
IMTP	500 Hz	Two trials (180 s rest)	Peak RFD = Maximal tangential slope over any two adjacent samples	(Haff et al., 1997)
IMTP	600 Hz	Four trials (180 s rest)	Peak RFD = Maximal tangential slope over any two adjacent samples	(Haff et al., 2005)
IMTP	600 Hz	Four trials (180 s rest)	Peak RFD = Maximal tangential slope over any two adjacent samples	(Haff et al., 2008)
IMTP	500 Hz	Two trials (180 s rest)	Peak RFD = Maximal tangential slope over any two adjacent samples	(Kawamori et al., 2006)
IMTP	1000 Hz	Two trials 3 s (120 s rest)	Slope of the force time = Mean RFD 0-50, 0-100, 0-150, 0-200 and 0-250 ms	(Khamoui et al., 2011)

			using slope of force time curve for the allotted duration	
IMTP	960 Hz	Three trials 5 s (180 s rest)	Peak RFD = Maximal tangential slope over any two adjacent samples	(McGuigan and Winchester, 2008)
IMTP	960 Hz	Three trials 5 s (180 s rest)	Peak RFD = Maximal tangential slope over any two adjacent samples	(McGuigan et al., 2010)
IMTP & Squat	1000 Hz	Three trials 3 seconds (180 s rest)	Peak force divided by time to peak force = Mean RFD	(Nuzzo et al., 2008)
IMTP	500 Hz	Two trials (180 s rest)	Peak RFD = Maximal tangential slope across a 5 ms window	(Stone et al., 2003b)
IMTP	600 Hz	Two to three trials	Peak RFD = Maximal tangential slope across a 5 ms window	(Stone et al., 2004)
IMPT	1000 Hz	Three trials of 5 s	Peak RFD = Maximal tangential slope across two adjacent data points	(West et al., 2011)
IMTP	500 Hz	Two trials of 3 s (180 s rest)	Peak RFD = Maximal tangential slope across a 5 ms window	(Wilson et al., 1995)
*Cannot be the same as the method used to calculate RFD during the squat jump, as this was the slope of the force time curve for the propulsion phase, but could be the slope of the force time curve from onset to peak force.				

Similarly, during multi-joint dynamic assessments of RFD the terms maximum RFD and peak RFD are also used interchangeably, within the literature, with some authors only referring to RFD and not specifically stating if this refers to mean or peak RFD (Table 3.3), in these situations the authors calculate RFD by slope of the force time curve (change in force / time (Cormie et al., 2010b; Cormie et al., 2010a; Khamoui et al., 2011)) resulting in mean RFD rather than peak RFD.

Table 3.3 Dynamic Multi-joint Assessment

Activity	Sampling Frequency	Time Period	Calculation Method	Authors
Unilateral CMJ	1000 Hz	n/a	0-150 ms using slope of force time curve for the allotted duration = Mean RFD	(Burgess et al., 2007)
Squat Jump	1000 Hz	n/a	Slope of the force time curve for the propulsion phase = Mean RFD	(Cormie et al., 2010a)
Squat Jump	1000 Hz	n/a	Slope of the force time curve for the propulsion phase = Mean RFD	(Cormie et al., 2010b)
MTP	500 Hz	Two trials (180 s rest)	Peak RFD = Maximal tangential slope over any two adjacent samples*	(Haff et al., 1997)
MTP	600 Hz	Two trials (180 s rest)	Peak RFD = Maximal tangential slope over any two adjacent samples*	(Haff et al., 2005)
MTP	600 Hz	Two trials (180 s rest)	Peak RFD = Maximal tangential slope	(Haff et al., 2008)

			over any two adjacent samples*	
SJ & CMJ	500 Hz		Peak RFD = Maximal tangential slope over any two adjacent samples	(Haff et al., 2000)
MTP	500 Hz	Two trials (180 s rest)	Peak RFD = Maximal tangential slope over any two adjacent samples	(Kawamori et al., 2006)
High Pull MTP	1000 Hz	n/a (210 s rest)	Slope of the force time curve for the propulsion phase = Mean RFD 0-50, 0-100, 0-150, 0-200 and 0-250 ms using slope of force time curve for the allotted duration = Mean RFD	(Khamoui et al., 2011)
CMJ	1000 Hz	Three trials (180 s rest)	Peak RFD = Maximal tangential slope over any two adjacent samples Mean RFD = Peak force / time to peak force	(McLellan et al., 2011b)
CMJ	1000 Hz	Three trials (180 s rest)	Peak RFD = Maximal tangential slope over any two adjacent samples	(McLellan and Lovell, 2012)

Mid-Thigh Pull (MTP)

*System mass not applied to force platform prior to commencing movement, bar resting on support bars

As with isometric multi-joint assessment of RFD, when peak RFD is stated it has been calculated as the maximal tangential slope over any two adjacent samples (Table 3.2), however, the range of sampling frequencies between studies (500-1000 Hz) will affect the precision of such measures. In contrast, when specific epochs are used, the calculation provided results in mean RFD for the specific epoch using slope of force time curve for the allotted duration (Table 3.3). Only McLellan et al. (2011b, 2012) defines the different calculations used for mean and peak RFD.

Additionally, when using the mid-thigh pull, Haff et al. (1997, 2005, 2008) did not include system mass in the calculation, as the bar was resting on a rack prior to commencing the lift. In turn this may amplify the RFD as the load is applied to the force plate as the lift is initiated, compared to when system mass is applied to the force plate at the start of the activity, as has been shown with the calculation of power (Cormie et al., 2007a; Cormie et al., 2007c; Cormie et al., 2007b; Hori et al., 2007).

3.2.6 Rate of Force Development and Impulse

Rate of force development refers to the amount of force produced over a period of time and is therefore calculated as the slope of the force time curve (Δforce/Δtime). In contrast, impulse represents a change in momentum and is calculated as force multiplied by time ($\Delta F \bullet \Delta t$) and can be used to calculated the change in velocity (acceleration) of a given mass (Lake et al., 2014b). This is commonly used in the calculation of velocity of system centre of mass when calculating power applied to the system using forward dynamics (Cormie et al., 2007a;

Cormie et al., 2007c; Haines et al., 2010; Kirby et al., 2011; McBride et al., 2011; Lake et al., 2012; Lake et al., 2014a) (Discussed in detail in section 3.1.1).

As both mean RFD and impulse can be calculated over different time epochs, appropriate to the time frames available for force production in sporting situations, they generally demonstrate moderate to strong associations with athletic tasks including jumping and sprinting (Sleivert and Taingahue, 2004; Hunter et al., 2005; McBride et al., 2010; Kirby et al., 2011; McLellan et al., 2011b; Floria and Harrison, 2013b), although peak RFD (Haff et al., 2015) and impulse at 200 ms (Comfort et al., 2015) appear to be the most reliable. With Sleivert and Taingahue (2004) reporting a moderate inverse correlation (r= -0.64) between net vertical impulse and 5 m sprint time, with Hunter et al. (2005) reporting strong associations between both vertical (r=0.76) and horizontal impulse (r=0.78) and sprint velocity during the acceleration phase.

Change in impulse may be a key determinant of adaptation to a training stimuli because of this relationship with motion (Weyand et al., 2000; Wright and Weyand, 2001; Hunter et al., 2005; Knudson, 2009), especially when considering jump performances if calculating jump height based on the impulse-momentum relationship (Knudson, 2009; McBride et al., 2010; Kirby et al., 2011). Increased impulse is likely to result in an increase in athletic performance, due to the fact that it results in greater acceleration of the mass that it is applied to; usually body mass during sprinting and jumping. As such, assessment of impulse and peak RFD may be useful measures in the identification of adaptations to training and subsequent reductions in performance post competition, as previously highlighted (McLellan and Lovell, 2012).

3.2.7 Summary

Based on the differences within the methods of calculating RFD it is suggested that future research clearly identifies whether peak RFD, or mean RFD has been calculated and that these terms are clearly used within the text, with the exact methods described in detail within the methods. It would also be beneficial for future research to clearly identify the effect that sampling frequency has on the assessment and calculation of both peak and mean RFD. Furthermore, determining if RFD or impulse is a more reliable measure to monitor changes in performance, while identifying which of these two force-time characteristics demonstrates a stronger association with a variety of athletic performances would also be useful for researchers and practitioners alike.

Future investigations should also determine if system mass should be applied to the force platform prior to initiation of movements, as with assessment of power output (Cormie et al., 2007a; Cormie et al., 2007c; Hori et al., 2007; McBride et al., 2011).

3.3 Olympic Lifts and their Component Lifts

Olympic lifts consist of the snatch and the clean and jerk, with Strength and Conditioning Coaches incorporating numerous variations of these exercises into their athletes' training programmes. Variations of the Olympic lifts are usually performed with the intent to move as rapidly as possible for 4-8 sets of 1-6 repetitions at loads of 75-90% 1-RM (Baechle et al., 2008).

In competition the snatch and clean are performed with the athlete catching the bar in a full depth squat. In contrast, in training the power snatch and power clean are commonly used as substitutes, where the athlete catches the bar in a quarter squat positions; or alternatively can be caught in a split stance. Further variations of the clean can be seen in the starting position of the lift, where the bar can begin on the floor (as in competitive lifting), in the hang position (from just above the patella, with the athlete in what represents the mid-point of a Romanian Deadlift, with the shoulders in front of the bar), or from mid-thigh (bar resting mid-thigh while the athlete is in a semi-squatting position, with the shoulders directly above the bar). Variations of these Olympic lifts are commonly used to enhance power development during sports-specific movements (rapid extension of ankles, knees and hips) (Stone, 1993; Stone et al., 2003a; Stone et al., 2003b; Stone et al., 2007).

3.3.1 Relationships with Athletic Performance

Performance, defined as maximal load successfully lifted (1-RM), in the power clean and its derivatives have been shown to be strongly associated with athletic performance (Hori et al., 2008; Brechue et al., 2010). Hang power clean 1-RM performance has been shown to be related to sprint, change of direction and jump performance (Hori et al., 2008), with relative power clean performance (1-RM/body mass) demonstrating a stronger association ($r = 0.68$, $r = 0.58$; $p \leq 0.01$) with average running velocity over 9.1 m and 18.3 m, compared to relative back squat performance ($r = 0.53$, $r = 0.50$; $p \leq 0.01$) (Brechue et al., 2010). Similarly, we recently reported that ratio scaled power clean performances were inversely related (r -0.625, r -0.558, r -0.620) to 5 m, 10 m and 20 m sprint times, in professional rugby league athletes (Comfort and Pearson, 2014). Such associations may be explained by the similar kinetics between Olympic style lifts (second pull phase of the hang snatch) and squat jump performances (Canavan et al., 1996), which may also explain the links with sprint performances due to the rapid force production from combined hip and knee extension and plantar flexion (Weyand et al., 2000; Wright and Weyand, 2001; Hunter et al., 2005; Weyand et al., 2006; Weyand et al., 2010).

3.3.2 Kinematic Assessment of the Olympic Lifts

During Olympic lifting competitions it has been identified that peak bar velocity (calculated from displacement time data) and peak power output (calculated from system mass and acceleration of the bar) occurs during the second pull phase (from mid-thigh until the end of the triple extension phase) of the clean (Garhammer, 1979, 1980, 1982, 1991; Pennington et al., 2010). More recently similar findings have been observed in competitive weightlifters using both two and three-dimensional motional capture to analyse the Snatch (Isaka et al., 1996; Gourgoulis et al., 2000; Gourgoulis et al., 2002; Pennington et al., 2010; Hadi et al., 2012; Harbili, 2012; Harbili and Alptekin, 2014), where power output was assessed using the same methods as Garhammer (1993).

Data collected on seven elite Weightlifters at the 1975 United States National Championships revealed that the second pull phase of the lift resulted in the highest barbell velocity and therefore power output, with values >4000 W in the ≥100kg athletes (Garhammer, 1980). It must be noted that barbell velocity was calculated using displacement time data from video (25 fps), with power subsequently calculated using an inverse dynamics approach (See Chapter 3.1 for a detailed discussion of methods of assessing power output). A further analysis of five gold medallist Weightlifters at the 1984 Olympic Games revealed a similar trend in power development, with maximal barbell velocity occurring during the second pull phase of the clean and snatch, and comparable power outputs in both the clean and the jerk phases of the clean and jerk (Garhammer, 1985). In contrast to the previous study, power outputs of >5000W were observed in the 97.7kg lifter during both the clean and the jerk, and >6000 W in the 138.5kg lifter, although this may be partly explained by the use of a higher frame rate (50 fps) resulting in higher and more precise barbell velocities. Garhammer (1991) went on to compare the data from the male athletes, presented in the two studies above, to the performances of the nine female gold medal winning Weightlifters at the first Women's World Weightlifting Championships in 1987. Results demonstrated that both men and women generate the greatest barbell velocities and power in the second pull phase of the clean and snatch, and that peak power during the jerk is comparable to second pull phase of the clean. Absolute average power outputs during the snatch and the clean were noticeably greater in the men compared to the women, and remained greater when ratio scaled for both the snatch (34.4±2.5 W/kg, 22.5±1.7 W/kg; respectively) and the clean (34.2±3.6 W/kg, 21.0±1.8 W/kg; respectively). Average power during the second pull phase of both the snatch (Men 52.7±4.5 W/kg vs. Women 40.1±5.0 W/kg) and clean (Men 52.5±8.9 W/kg vs. Women 38.2±3.3 W/kg) showed comparable trends between lifts and sexes.

3.3.3 Kinetic Assessment of the Olympic Lifts

Only three observational studies have previously reported kinetic variables during the different phases of the Olympic lifts, finding that the greatest vertical ground reaction force, which have described the peak forces during the first pull, transition and second pull phases (Enoka, 1979; Hakkinen et al., 1984; Souza et al., 2002). Enoka (1979) reported a peak force of 2809 N during the second pull phase of the clean, in five experienced Olympic weightlifters, with Hakkinen et al. (1984) finding similar results in 13 weightlifters performing the clean across a range of loads. More recently Souza et al. (2002) conducted the first study to investigate the forces during the different concentric phases of the power clean. Ten collegiate weightlifters, performed power cleans at 60% and 70% 1-RM, while standing on a force platform, with results confirming previous observations in the clean and snatch, that peak forces, as high as 2336 N, are observed during the second pull phase.

Two previous studies had also reported similar trends in force development during the snatch and hang snatch (Garhammer and Gregor, 1992; Canavan et al., 1996). Garhammer and Gregor (1992) compared force time characteristics in four Olympic weightlifters during performance of the snatch and countermovement jumps. The jump performances were performed during the warm up period and the two heaviest successful snatches performed during the training session were analysed for comparison. Results revealed similarities in force time curves and maximum propulsion force developed between both movements. Unfortunately, there was no specific statistical analysis of the data presented in this investigation, just a description of the trends. Canavan et al. (1996) compared kinetics (peak power, time to peak power, relative peak power, peak force and time to peak force) between the hang snatch and the squat jump in trained male athletes (n=7). Data was collected with athletes performing all exercises while standing on a force platform and power calculated via forward dynamics. The authors reported significant relationships between exercises for all kinetic variables, although they fail to state any specific correlations. Unfortunately the authors did not perform any statistical analyses to determine if there was a significant difference between values. More recently similar findings have been observed in competitive weightlifters using both two and three-dimensional motional capture to analyse the Snatch, albeit with inverse dynamics used to calculate peak power output based on bar velocity (Isaka et al., 1996; Gourgoulis et al., 2000; Gourgoulis et al., 2002; Pennington et al., 2010; Hadi et al., 2012; Harbili, 2012; Harbili and Alptekin, 2014).

3.3.4 Summary

The previous studies appear to demonstrate that the greatest force and power (calculated using inverse dynamics) is generated during the second pull phase of the snatch (Garhammer, 1980, 1985, 1991; Garhammer and Gregor, 1992; Canavan et al., 1996; Hadi et al., 2012; Harbili, 2012; Harbili and Alptekin, 2014), clean (Enoka, 1979; Garhammer, 1982; Hakkinen et al., 1984; Garhammer, 1985, 1991) and power clean (Souza et al., 2002), however, this may be due to the fact that the bar has already gaining momentum during the first pull and transition phases. It can be observed that the joint kinematics of the snatch and the clean along with the power clean and power snatch are very similar during the concentric phases, which may explain the similarities in these findings.

3.3.5 Areas for Further Research

No research has compared the peak force or peak RFD, during the power clean, hang power clean (bar held just above the patella in the start position and caught in a shallow front squat) the mid-thigh power clean (bar held at mid-thigh in the start position and caught in a shallow front squat) and the mid-thigh clean pull (this is the concentric phase of the mid-thigh power clean without the catch phase). Furthermore, no studies have compared peak power during the power clean, hang power clean and mid-thigh power clean to establish which generates the greatest power. The power clean was selected as this is more commonly used in the training of athletes from a variety of sporting backgrounds, as it is generally thought to be easier to learn than the snatch and does not require as much technical excellence or rely on the large range of motion required for performance of the clean.

3.4 Optimal Loading for Peak Power Output

Mechanical power can be defined as the force applied to an object multiplied by the velocity of the movement, or work divided by the time required to complete the given work:

Power = Force x (Distance/Time)

Power = Force x Velocity

Power = Work / Time

Therefore, both force applied to an object and the resultant velocity play an integral role in power output, with peak power occurring as a compromise between peak force and peak velocity (Wilkie, 1949; Siegel et al., 2002; Kawamori and Haff, 2004). In general, peak force occurs during isometric conditions (zero velocity) where as peak velocity occurs with no external load.

Numerous studies have been concerned with the load which elicits peak power output across a range of exercises including the clean variations (Kawamori et al., 2005; Kawamori et al., 2006; Cormie et al., 2007c; Cormie et al., 2007b; Cormie et al., 2007e; Kilduff et al., 2007), squat (Cormie et al., 2007c; Cormie et al., 2007b; Cormie et al., 2007e) squat jump (Baker et al., 2001; Cormie et al., 2007a; Cormie et al., 2007c; Cormie et al., 2007b; Cormie et al., 2007e) and bench press (Izquierdo et al., 1999; Baker, 2001; Izquierdo et al., 2002; Jandacka and Uchytil, 2011). The optimal loads which elicit peak power output for the power clean (Cormie et al., 2007c; Cormie et al., 2007b; Cormie et al., 2007e), hang power clean (Kawamori et al., 2005; Kilduff et al., 2007) and mid-thigh power clean (Kawamori et al., 2006) have been reported between 60-80% one repetition maximum (1-RM) power clean, although these were generally not significantly different at loads ±10% of the optimal load, when forward dynamics is used to assess peak power. In contrast, Pennington et al. (2010) found no significant difference ($p>0.05$) in peak power output between 80-100% 1-RM in both the power clean and power snatch. It must be noted, however, that power was calculated using inverse dynamics which has been shown to substantially alter both power output and the load which elicits peak power (Cormie et al., 2007c; Cormie et al., 2007b; Cormie et al., 2007e; Hori et al., 2007) (See Chapter 3.1).

3.4.1 Optimal Loading during Single Joint Exercises

Early research by Kaneko et al., (1983) revealed that peak power output occurred at 30% of maximal voluntary isometric contraction (MVIC) during elbow flexion and that adaptations to training were specific to the force-velocity requirements of the training mode, whereby the greatest adaptations were observed at the velocity at which the participants trained. Toji, Suei and Kaneko (1997) progressed this research by conducting a training study to determine if training at 0% and 30% MVIC or 30% and 100% MVIC would result in specific adaptations in force, velocity and power in 12 male subjects. Results demonstrated that MVIC increased only in the high force group, whereas velocity improved in both groups, concluding that higher loads were advantageous in terms of adaptations across the force velocity profile. A subsequent study investigated the effects of multiple load training (30% and 60% MVIC, 30% and 100% MVIC, and 30%, 60% and 100% MVIC), with repetitions matched between groups (Toji and Kaneko, 2004). The authors concluded that multiple load training (30%, 60% and 100% MVIC) resulted in the greatest increases in force, velocity and therefore power in single joint movements, in line with the recent recommendations for power development by Haff and Nimphius (2012). Application of these single joint studies, based on percentage of MVIC is clearly limited in terms of its practical application to dynamic tasks (e.g. squats, squat jumps, Olympic lifts) that are usually performed during athletic conditioning where maximal strength is usually assessed via one repetition maximum testing and not MVIC.

3.4.2 Optimal Loading during Squats

Izquierdo et al (1999) investigated the strength and power characteristics in middle aged (n = 26, mean age 46 years) and elderly men (n = 21; mean age 65 years), assessing power across a spectrum of loads (0, 15, 30, 45, 60, 70% 1-RM) during the Smith-machine half squat, revealing that peak power occurred between 60-70% 1-RM, with no differences between groups. A subsequent study by the same group of researchers found that 1-RM Smith-machine half squat significantly increased along with peak power output during the half squats across a spectrum of loads (15, 30, 45, 60, 70% 1-RM) after 16 weeks of strength training in middle aged (46 ± 2 yr) and older (64 ± 2 yr) men (Izquierdo et al., 2001b). Both pre and post training the participants' peak power occurred between 60-70% 1-RM, as reported in their previous study (Izquierdo et al., 1999). A further study using the same methods in middle aged (n = 26, mean age 46 yr) and elderly men (n = 21, mean age 64 ± 2 yr) also reported peak power occurred between 60-70% 1-RM, although the younger and stronger group developed peak power at 60% 1-RM where as the older and weaker group developed peak power at 70% 1-RM, highlighting a decline in force and power production with increasing age (Izquierdo et al., 2001a). It is worth noting however, that power in the aforementioned studies was calculated using inverse dynamics and excluded body mass in the calculation resulting in very low power values, (the implications of such methods of assessing power are discussed in detail in Chapter 3.1).

Siegel et al. (2002) used college age resistance trained subjects (n=25) to investigate the load which elicits peak power during squats performed on a Smith machine, with power calculated using inverse dynamics and related this to muscle fibre distribution from muscle biopsies of the vastus lateralis. Results revealed that peak power occurred between 50-70% 1-RM, similar to the findings in older subjects (Izquierdo et al., 1999; Izquierdo et al., 2001a; Izquierdo et al., 2001b), but no relationships between performance measures and muscle fibre distribution were observed. Similar findings were observed in well trained male sprinters (n=10), with half squats performed on a Smith machine. Power was calculated from the product of vertical ground reaction force (assessed using a force plate) and bar velocity (assessed using a LPT), revealing that peak power occurred at 60% 1-RM (3134.3 ± 561.9 W) although this was not significantly different ($p>0.05$) when compared to peak power at any other load (30, 45, 60, 70, 80% 1-RM). While the Smith machine improves the accuracy of the assessment of velocity by preventing any horizontal displacement of the bar, it limits the application of these findings to free weight back squats, which are more commonly performed during strength training programmes. It is also worth noting that using combined kinetic (force collected via the force platform) and kinematic (velocity calculated via bar displacement time data) methods to calculate power are limited, as Lake et al. (2012) revealed that velocity of the bar does not reflect velocity of the COM of the body or system.

Zink et al. (2006) investigated the effects of load (20-90% 1-RM in 10% increments) on peak power, force and barbell velocity during free weight back squats, in 12 experienced lifters. The authors observed no significant difference ($p>0.05$) in peak power output across loads, although the highest values occurred at 40-50% 1-RM. There was, however, a progressive increase in peak ground reaction force and a progressive decrease in bar velocity with an increase in load. The slightly lower PMax loads in this study compared to the aforementioned studies may be explained by the fact that this was the only study to assess free weight back squat performance, along with the use of older, less well trained participants in the previous studies (Izquierdo et al., 1999; Izquierdo et al., 2001a; Izquierdo et al., 2001b).

Cormie et al. (2007c) compared six different methods of assessing power during squats, squat jumps and power cleans across a spectrum of loads: one linear position transducer (LPT) (including barbell mass), one LTP (including system mass), two LPT's, FP only, FP plus one LPT and a FP plus two LPT's, in well trained males. Results demonstrated that one LPT plus barbell mass under-valued force and therefore power during the squat and jump squat, where as the one LPT and two LPT methods (including system mass) over-valued force and therefore power in line with the findings of Hori et al. (2007) during the hang power clean and squat jump. During the squat, the use of 1 LPT and 2 LPT's resulted in the identification of an optimal load of 30% 1-RM (4215.07 ± 1227.11 W; 4104.24 ± 1162.01 W, respectively), whereas the methods using kinetic data (FP, FP plus 1 LPT) identified optimal load as 71% 1-RM (3243.66 ± 448.78 W, 3291.28 ± 326.41 W, respectively) and (FP plus 2 LPT) 56% (3206.32 ± 411.49 W), although peak power values differed across all methods. The authors conclude that methods of assessing power need to be standardised to ensure that findings between studies are comparable. These findings and recommendations for the back squat have been supported by a series of other studies published by these authors (Cormie et al., 2007a; Cormie et al., 2007b; Cormie et al., 2007e; McBride et al., 2011).

These results appear to demonstrate that peak power output during squats occur across a spectrum of loads, which is influenced by the methods used to assess power (kinetic, kinematic or combined methods), the mode of activity (free weight versus Smith machine) and possibly training status. If assessed during free weight back squats in trained individuals peak power appears to occur between

40-50% 1-RM if assessed based on bar velocity (inverse dynamics) (Zink et al., 2006), or ~70% if assessed from force time data (forward dynamics) (Cormie et al., 2007c; Cormie et al., 2007b).

3.4.3 Optimal Loading during Squat Jumps

Baker (2001) reported that peak power output during squat jumps was achieved at 46-51% of 1-RM in stronger rugby league athletes, compared to 58-69% 1-RM in the weaker rugby league athletes. Power output, however, was calculated from bar velocity and system mass using inverse dynamics which has been shown to result in an altered PMax load (Cormie et al., 2007a; Cormie et al., 2007c; Cormie et al., 2007b; Cormie et al., 2007e; McBride et al., 2011).

Stone et al. (2003a) investigated the effects of loading (10-90% 1-RM in 10% increments) on power output, calculated from bar velocity using inverse dynamics, during vertical jumps in trained subjects. Peak power output occurred in the 10% condition in both the squat jump (5113.07 ± 1482.17 W) and countermovement jump (5199.73 ± 1301.06 W), with a progressive decline in power output with an increase in load. When subjects were divided in to the weakest (n=5) and the strongest (n=5) peak power output occurred at 10% 1-RM whereas peak power occurred at 40% 1-RM in the strong group. The differences in optimal loading between the studies of Baker (2001) and Stone et al. (2003a) are likely due to the higher strength levels in the rugby league players in the earlier study, as both studies highlight that maximal strength can affect the load which elicits peak power during squat jumps. More recently, however, Lake et al. (2012) have suggested that barbell kinematics should not be used to assess power during squat jumps as it does not reflect displacement or velocity of the system CoM, and therefore leads to overestimation of velocity resulting in an elevated power values which was 18.7% greater than the power assessed via forward dynamics.

As previously mentioned, Cormie et al. (2007c) compared six different methods of assessing power during squats, squat jumps and power cleans across a spectrum of loads, in well trained males. Results demonstrated that one LPT plus barbell mass under-valued force and therefore power during the squat and jump squat, where as the one LPT and two LPT methods (including system mass) over-valued force and therefore power in line with the findings of Hori et al. (2007) during the hang power clean and squat jump. During the squat jump, the use of 1 LPT and mass resulted in a PMax load of 42% 1-RM (3379.56 ± 505.84 W), whereas all other methods identified body mass (no external load) as PMax load 6260.95-6496.95 W). The authors conclude that methods of assessing power need to be standardised to ensure that findings between studies are comparable. These findings and recommendations for the squat jump have been supported by a series of other studies published by these authors (Cormie et al., 2007a; Cormie et al., 2007b; Cormie et al., 2007e; McBride et al., 2011).

A recent study by Turner et al. (2012) found peak power output (calculated from the product of vertical ground reaction force and bar velocity) and peak bar velocity to occur at 20% 1-RM, in well trained rugby players, although this was not significantly ($p>0.05$) greater than the 30% 1-RM load; unfortunately they did not use loads <20% 1-RM. Unsurprisingly, peak vertical ground reaction force occurred at 100% 1-RM. Our work (Thomasson and Comfort, 2012; Comfort et al., 2013a) however, found that peak power output during squat jumps, calculated using forward dynamics, occurred at body mass (no external load) although this was not significantly different to the 10 and 20% loading conditions, in both well trained rugby league players and collegiate level athletes, in line with previous findings (Cormie et al., 2007c; Cormie et al., 2007b; Cormie et al., 2007e; Cormie et al., 2008; McBride et al., 2011).

More recently, Pazin (2013) compared the peak power, peak force and peak velocity (of centre of mass) across loads (0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3 x body mass) during both squat jumps and countermovement jumps in male subjects (n=40). Loading was varied by the use of elastic resistance, to either add to or subtract load from body mass. Dependant variables were assessed with participants standing on a force plate with power calculated using forward dynamics. Results demonstrated that peak power was achieved at body mass, with no difference between strength trained athletes (n=10), speed trained athletes (n=10), physically active non-athletes (n=10) and sedentary individuals (n=10).

As with the findings for PMax loads during the squat, the mode of exercise (machine versus free weight) appears to influence the PMax load, with the use of a machine resulting in a increase in both 1-RM performance and PMax load (Harris et al., 2007; Harris et al., 2008). Harris et al. (2007) used forward dynamics to assess power output during loaded (10-100% 1-RM) squat jumps, performed on a modified hack squat machine, in national level rugby players. Results demonstrated that individual peak power output occurred at 39 ± 8.6% 1-RM. Interestingly, a change in load ±20% either side of the individuals PMax load resulted in only a small change (9.9 ± 2.4%) in peak power output. It is worth noting that these subjects were very strong (relative 1-RM 2.67 ± 0.46 kg/kg), which along with the use of a machine, may have resulted in the increased PMax load compared to previous studies (Stone et al., 2003a; Stone et al., 2003b; Cormie et al., 2011b; Cormie et al., 2011a; Thomasson and Comfort, 2012; Comfort et al., 2013a).

From the results of these studies it would appear that peak power output, during squat jumps, occurs at or around body mass (no external load) when assessed using forward dynamics (Cormie et al., 2007a; Cormie et al., 2007c; Cormie et al., 2007b; Cormie et al., 2007e; Cormie et al., 2008; Pazin et al., 2013), although there may be some variation between individuals, especially if very strong (Harris et al., 2007; Harris et al., 2008). It is also worth noting that during such exercises, performed at PMax loads, it is possible to perform a greater number of repetitions than those usually recommended (1-5 repetitions) for power development, with Thomasson and Comfort (2012) finding no decrease in performance during sets of 6 repetitions performed at body mass (PMax load), 20% and 40% 1-RM, with a more recent study finding no decrement in performance during 10 repetitions performed at body mass (PMax load), 10%, 20%, 30% and 40% 1-RM (Comfort et al., 2013a).

3.4.4 Optimal Loading during the Power Clean and its Variations

During Olympic weightlifting competitions it has been identified that peak bar velocity (calculated from displacement time data) and peak power (calculated from system mass and acceleration of the bar) occurs during the second pull (from mid-thigh until the end of the triple extension phase) phase of the clean (Garhammer, 1979, 1980, 1982, 1985, 1991; Pennington et al., 2010). More recently similar findings have been observed in competitive weightlifters using both two and three-dimensional motional capture to analyse the Snatch (Isaka et al., 1996; Gourgoulis et al., 2000; Gourgoulis et al., 2002; Pennington et al., 2010; Hadi et al., 2012; Harbili, 2012), where power was assessed using the same methods as Garhammer (1993) (Methodological issues of assessing power are discussed in detail in Chapter 3.1).

Variations of the power clean are regularly incorporated in athletes' training regimes, with specific potential benefits hypothesised for each variation of the clean, although many of these theoretical benefits have not been substantiated by empirical evidence. For example it has been observed that the transition phase (double knee bend) results in an unweighting phase representative of a countermovement, which may result in an increase in force production and power output due to utilisation of the stretch shorten cycle (Enoka, 1979; Garhammer, 1980; Garhammer, 1982; Hakkinen et al., 1984; Garhammer and Gregor, 1992), however, no research has compared kinetic performances in the power clean performed from the hang position with the mid-thigh position. In contrast, numerous studies have investigated the load which elicits peak power output across a range of exercises including the clean variations (Kawamori et al., 2005; Kawamori et al., 2006; Cormie et al., 2007c; Cormie et al., 2007b; Cormie et al., 2007e; Kilduff et al., 2007). The optimal loads which elicit peak power output for the power clean (Cormie et al., 2007c; Cormie et al., 2007b; Cormie et al., 2007e), hang power clean (Kawamori et al., 2005; Kilduff et al., 2007) and mid-thigh power clean (Kawamori et al., 2006) have been reported between 60-80% one repetition maximum (1-RM) power clean, although these were generally not significantly different at loads ±10% of the optimal load, when forward dynamics is used to assess peak power. In contrast, Pennington et al. (2010) found no significant difference ($p>0.05$) in peak power output between 80-100% 1-RM in both the power clean and power snatch, although it must be noted that power was calculated using inverse dynamics which has been shown to substantially alter both power output and the load which elicits peak power (Cormie et al., 2007c; Cormie et al., 2007b; Cormie et al., 2007e; Hori et al., 2007).

3.4.4.1 Power Clean

Cormie et al. (2007c) compared six different methods of assessing power during squats, squat jumps and power cleans across a spectrum of loads: one linear position transducer (LPT) (including barbell mass), one LTP (including system mass), two LPT's, force platform (FP) only, FP plus one LPT and a FP plus two LPT's, in well trained males. The power cleans were performed at loads of 30-90% 1-RM at 10% increments. The differences in the power outputs calculated via the different methods are illustrated by the optimal load for power output occurring at different loads across methods. During the power clean, the kinematic only data (1 LPT and 2 LPT) under-valued force resulting in identification of an optimal load of 30% 1-RM, whereas the methods using kinetic data (FP, FP plus 1 LPT and FP plus 2 LPT) identified optimal load as 80% 1-RM, although the actual peak power values differed across all methods, although not significantly different to loads ±10% of the optimal load. Another study by Cormie et al. (2007e) investigated the optimal loading for peak power output during the squat, jump squat and power clean in twelve male athletes, with the power cleans performed across loads of 30-90% 1-RM at 10% increments. Force was determine via a force platform which the athletes stood on during the lifts, with bar velocity determined via two LPT's as previously described (Cormie et al., 2007c); results demonstrated again that peak power was achieved at 80% 1-RM, again with no significant differences ($p>0.05$) ±10% of the optimal load.

A further study by Cormie et al. (2007b) investigating the influence of the addition of body mass, body mass minus shank and foot mass on power output during the squat, squat jump and power clean across a range of loads, demonstrated that the exclusion of body mass results in a significant change ($p<0.05$) in power output and the load power relationship. Further supporting previous findings that body mass should be included in the calculation to ensure that force is not under-estimated and that methods of assessing power, during such exercises, should be standardised to ensure that findings are comparable (Cormie et al., 2007c; Hori et al., 2007). The subjects performed power clean at loads from 30-90% 1-RM in 10% increments, confirming that the peak power was achieved at 80% 1-RM, again with no significant differences (p>0.05) ±10% of the optimal load. The findings of the investigation revealed that the inclusion of body mass, or body mass minus shank mass did not affect the load that elicited peak power output in the power clean (80% 1-RM) or squat jump (no external load) where the entire body mass is accelerated throughout the exercise, although it did affect the results of the squat.

From the data currently available it would appear that the optimal load for the power clean is ~80% 1-RM, but that there is no significant difference (p>0.05) between performances at loads ranging from 70-90% 1-RM in trained athletes.

3.4.4.2 Hang Power Clean

Kawamori et al. (2005) assessed peak power output, in 15 collegiate athletes during the hang power clean, performed across a spectrum of loads (30-90% 1-RM hang power clean) at 10% increments, to identify the optimal load that elicits peak power output. Power was calculated from force time data collected via the force platform using forward dynamics to calculate the velocity of centre of mass of the system, with velocity at each time point multiplied by the corresponding force data. Subsequent analysis revealed that peak power and relative peak power (45.57 ± 5.20 W/kg) occurred at 70% 1-RM although this was not significantly different to the peak power output achieved across loads of 50-90% 1-RM. When the groups were divided into strong (1-RM ≥110 kg) and weak (1-RM <110 kg) the strong group achieved peak power (4281.15 ± 634.84 W) at 70% 1-

RM and the weak group achieved peak power (3982.58 ± 906.49 W) at 80% 1-RM, although these were still not substantially different to the peak power values achieved at 50-90% 1-RM.

Similar to the previous study Kilduff et al. (2007) compared peak power output during the hang power clean, across loads of 30-90% 1-RM, in twelve profession rugby union player. Force time data was collected via a force platform with power calculated using forward dynamics. The results demonstrated that peak power output (4467.0 ± 477.2 W) occurred at 80% 1-RM, although this was only significantly greater than the power output at 30% 1-RM (3246.0 ± 552.8 W), similar to the results from the stronger athletes in the study by Kawamori et al. (2005). In contrast peak force (3544.2 ± 551.9 N) occurred at 90% 1-RM; although this was not significantly different ($p>0.05$) compared to the 80% 1-RM load (3487.0 ± 526.6 N). Peak force at both 80% and 90% 1-RM were significantly greater ($p<0.05$) when compared to all of the other loads, with peak force progressively increasing in line with increased loading. Peak RFD (29858 ± 17663 N/s) also occurred in the 90% 1-RM condition, although this was not significantly different ($p>0.05$) compared to any of the other loads.

As with the power clean, from the available evidence it appears that there is a range of loads (50-90% 1-RM) at which peak power occurs during the hang power clean, with training status (defined by relative strength level) influencing the load at which peak power occurs. Peak power occurs between 70-80% 1-RM although this is not significantly different ($p>0.05$) compared to loads of ±10%.

3.4.4.3 Mid-thigh Clean Pulls

In a study investigating the relationships between strength and power performances in collegiate throwers Stone et al. (2003b) observed that peak power occurred during mid-thigh pulls at 30% MVIC (2065 ± 921 W) compared to 60% MVIC (1621 ± 589 W), with the difference remaining even after 8 weeks of strength and power training (30% MVIC = 2434 ± 683 W; 60% MVIC = 2178 ± 686 W). This is in line with previous findings during single joint movements (Kaneko et al., 1983; Moss et al., 1997; Toji et al., 1997; Toji and Kaneko, 2004).

More recently Kawamori et al. (2006) compared kinetics between the isometric mid-thigh pull and dynamic mid-thigh pull across a range of load (30, 60, 90, 120% 1-RM power clean), in eight male weightlifters. Peak power occurred in the 60% 1-RM condition (2228.9 ±192.3 W) although this was not significantly greater ($p>0.05$) than the other loading conditions. Isometric peak force (3177.5 ± 285.3 N) was greater than the 120% 1-RM condition (2604.5 ± 137.5 N), although this was not statistically significant ($p>0.05$). Peak force was significantly greater ($p<0.05$) in the 120% 1-RM conditioning compared to the lower loading conditions, with a progressive increase in peak force with an increase in load. In contrast, peak RFD occurred in the 30% condition (27607.4 ± 4608.3 N/s) and progressively decreased with an increase in load, although this was not statistically significant ($p>0.05$).

It is likely that the higher loads required to elicit peak power output in the power clean (80% 1RM) and hang power clean (70% 1RM) are due to the fact that the bar is displaced further, when compared to the mid-thigh power clean and MTCP (60% 1RM), resulting in an increased duration of force application and acceleration prior to the bar reaching the second pull (mid-thigh position) phase.

3.4.4.4 Summary and Applications

It is important to note, however, that although a substantial body research has been published investigating the load that elicits peak power output during a range of different exercise, this is not the panacea of power training. It is essential that each aspect of the force velocity continuum is considered during each mesocycle, with the primary aim of the phase being emphasised, but not at the expense of any other aspect of the force production (Newton and Kraemer, 1994; Newton et al., 2002; Cormie et al., 2011b; Haff and Nimphius, 2012).

3.4.5 Areas for Further Research

As the second pull phase of the Olympic lifts have been observed to result in the greatest force (Enoka, 1979; Hakkinen et al., 1984; Garhammer and Gregor, 1992; Souza et al., 2002), bar velocity and power (Garhammer, 1979, 1980, 1982, 1985) and the fact that strength and conditioning coaches regularly use various derivatives of the clean (e.g. power clean, hang power clean, mid-thigh power clean and mid-thigh clean pull) it would be useful to identify differences in force time characteristics between each of these variations. The results of such findings would permit strength and conditioning coaches to make more informed decisions regarding exercise selection.

The majority of previous research has been conducted using well trained team sport athletes or Olympic Weightlifters (Haff et al., 1997; Haff et al., 2005; Kawamori et al., 2005; Kawamori et al., 2006; Cormie et al., 2007c; Cormie et al., 2007b; Cormie et al., 2007e; Haff et al., 2008), and therefore the application of these findings to inexperienced athletes is problematic. Therefore, determining the effect of load and clean variation on force time characteristics in inexperienced female athletes would also be advantageous. An additional area for further research would is to determine the optimal load during the power clean in relatively inexperienced collegiate athletes, as previous research has focussed on well trained male athletes (Haff et al., 1997; Haff et al., 2005; Kawamori et al., 2005; Kawamori et al., 2006; Cormie et al., 2007c; Cormie et al., 2007b; Cormie et al., 2007e; Haff et al., 2008).

Finally identifying the effect of load on the kinetics and kinematics during the pulling variations of the clean (e.g. MTCP), to identify the optimal loads required to maximise specific force characteristics would be interesting, especially as the elimination of the catch phase permits loads >100% 1RM power clean. Interestingly, manipulation of load, across a larger range of loads, during the pulling variations of the clean, may permit appropriate stimuli across the entire force velocity continuum.

3.5 Research Hypotheses

1. Assessment of force time characteristics during power clean performances will be highly reliable
2. Peak force and peak RFD will be highest during the mid-thigh clean and mid-thigh clean pull, compared to the hang power clean and power clean, as this phase of the clean variations has been shown to elicit the greatest peak force and power during the clean and clean pull
3. Peak power output will be highest during the mid-thigh clean and mid-thigh clean pull, compared to the hang power clean and power clean, as this phase of the clean variations has been shown to elicit the greatest peak force and power during the clean and clean pull
4. Females will demonstrate greater peak force, peak RFD and peak power during the mid-thigh power clean, compared to the hang power clean and power clean as the mid-thigh variation has it requires less technical competency compared to the other variations. Additionally the mid-thigh power clean has previously been shown to elicit higher peak force, peak RFD and peak power when compared to the hang power clean and power clean
5. It was further hypothesised that peak power output would occur at 60% 1RM power clean, during the mid-thigh power clean, in line with previous research
6. Peak power output will occur at 70% 1RM power clean in inexperienced athletes, in line with previous research in well trained, more experienced athletes
7. During the mid-thigh clean pull, peak bar displacement, peak bar velocity and peak power will occur at 40% 1RM power clean, while peak force, impulse and peak RFD will occur at 140% 1RM power clean

4 Study 1

Within- and Between-Session Reliability of Power, Force and Rate of Force Development during the Power Clean

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Abstract

Although there has been extensive research regarding the power clean, its application to sports performance and its use as a measure of assessing changes in performance, no research has determined the reliability assessing the kinetics of the power clean across testing session. The purpose of this study, therefore, was to determine the within and between session reliability of kinetic variables during the power clean. Twelve professional rugby league players (age 24.5 ± 2.1 years; height 182.86 ± 6.97 cm; body mass 92.85 ± 5.67kg; 1-RM power clean 102.50 ± 10.35 kg) performed three sets of three repetitions of power cleans at 70% of their predetermined one repetition maximum power clean, while standing on a force plate, to determine within session reliability. This process was completed on three separate occasions, 4-5 days apart, to determine reliability between sessions. Intraclass correlation coefficients revealed a high reliability within sessions ($r \geq 0.969$) and between sessions ($r \geq 0.988$). Repeated measures analysis of variance showed no significant difference ($p>0.05$) in peak vertical ground reaction force, rate of force development and peak power between sessions, with small SEM's and SDD's for each kinetic variable (3.13 N, 8.68 N; 84.39 N/s, 233.93 N/s; 24.54 W, 68.01 W, respectively). Therefore, a change in peak force ≥ 8.68 N, rate of force development ≥24.54 N/s, and a change on peak power ≥68.01 W represent a real change in performance between sessions, in well trained athletes who are proficient at performing the power clean.

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4.1 Study 1 Commentary

Very small SDD may be due to the fact that strict controls were put in place during each testing session and between testing sessions, including visual analysis of force time curves to ensure that the force traces were representative of a power clean. In order to do this it was essential that the force time data represented stable system mass, prior to commencement of the lift and that two clear peaks occurred during the concentric phase of the lift, illustrating the first pull and second pull respectively. Any trials that did not meet these criteria was discounted and repeated after an appropriate rest period. Such strict criteria improve the scientific rigour of data collection procedures, but actually reduce ecological validity as such strict controls are unlikely to be used in a real world environment, especially when working in team sports with large numbers of athletes. It is likely that the implementation of such criteria dramatically improved the reliability and therefore resulted in such small SDD values for each variable.

Subsequent analysis of data revealed that a change in smoothing from 100 ms moving average to 400 ms moving average was shown not to noticeably affect peak force, peak RFD or peak power, which is likely due to the fact that all values were peak instantaneous values and not average measures. However, change from a 100 ms moving average to 400 ms moving average did help with analysis of force time data from subjects that showed a small amount of movement, based on assessment of the force time trace, prior to commencement of the lift, permitting an increase in sample size, due to inclusion of a greater number of subjects initially tested.

5 Study 2

Comparisons of Peak Ground Reaction Force and Rate of Force Development during Variations of the Power Clean

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Abstract

The aim of this investigation was to determine the differences in vertical ground reaction forces and rate of force development (RFD) during variations of the power clean. Elite rugby league players (n = 11; age 21 6 1.63 years; height 181.56 6 2.61 cm; body mass 93.65 6 6.84 kg) performed 1 set of 3 repetitions of the power clean, hang-power clean, mid-thigh power clean, or mid-thigh clean pull, using 60% of 1-repetition maximum power clean, in a randomized order, while standing on a force platform. Differences in peak vertical ground reaction forces (Fz) and instantaneous RFD between lifts were analyzed via 1-way analysis of variance and Bonferroni post hoc analysis. Statistical analysis revealed a significantly ($p<0.001$) greater peak Fz during the mid-thigh power clean (2,801.7 ± 195.4 N) and the mid-thigh clean pull (2,880.2 ± 236.2 N) compared to both the power clean (2,306.2 ± 240.5 N) and the hang-power clean (2,442.9 ± 293.2 N). The mid-thigh power clean (14,655.8 ± 4,535.1 $N.s^{-1}$) and the mid-thigh clean pull (15,320.6 ± 3,533.3 $N.s^{-1}$) also demonstrated significantly ($p<0.001$) greater instantaneous RFD when compared to both the power clean (8,839.7 ± 2,940.4 $N.s^{-1}$) and the hang-power clean (9,768.9 ± 4,012.4 $N.s^{-1}$). From the findings of this study, when training to maximize peak Fz and RFD the mid-thigh power clean and mid-thigh clean pull appear to be the most advantageous variations of the power clean to perform.

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5.1 Study 2 Commentary

With additional planning this study could have included peak power, as presented in study three, however, the initial aim of this study was to progress the work of Enoka et al. (1979) Hakkinen et al. (1984) Souza et al. (2002) , who had only investigated force and RFD during the clean and clean pull. Further development of this study and its themes led to the planning of study 3, with the inclusion of peak power.

5.2 Erratum

The figures within the published article (Figures 4 and 5 within the published manuscript) did not have the significance levels highlighted; this has been amended (Figures 5.1 and 5.2).

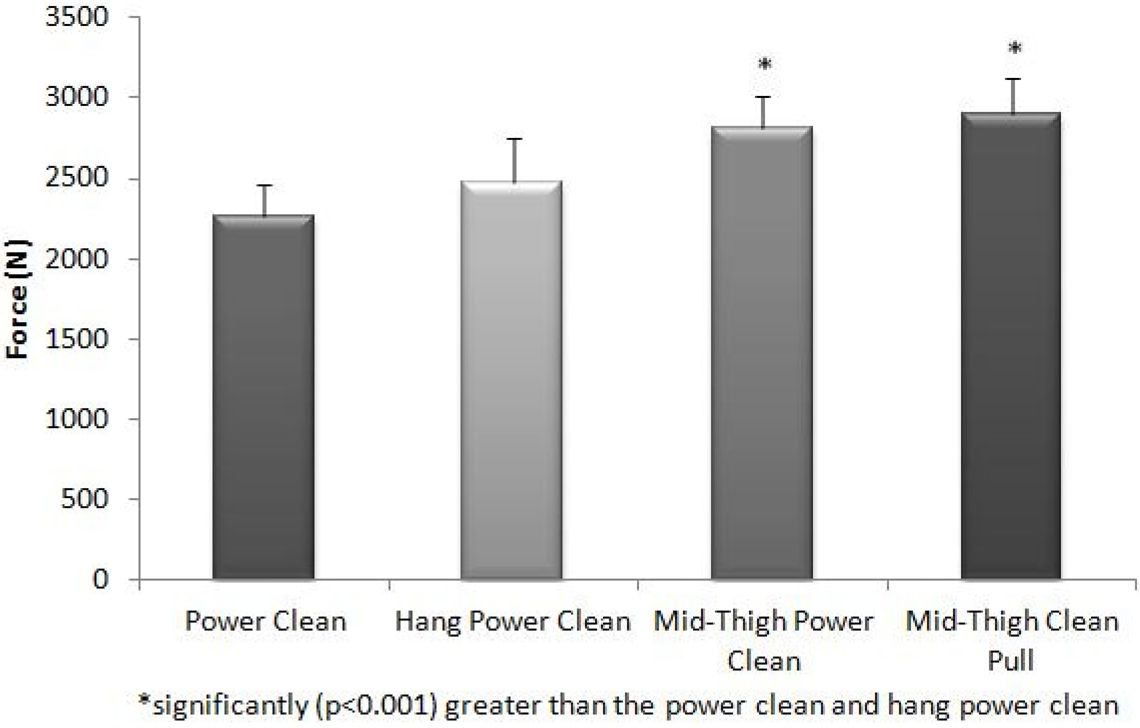

Figure 5.1: Comparison of peak force during variations of the power clean

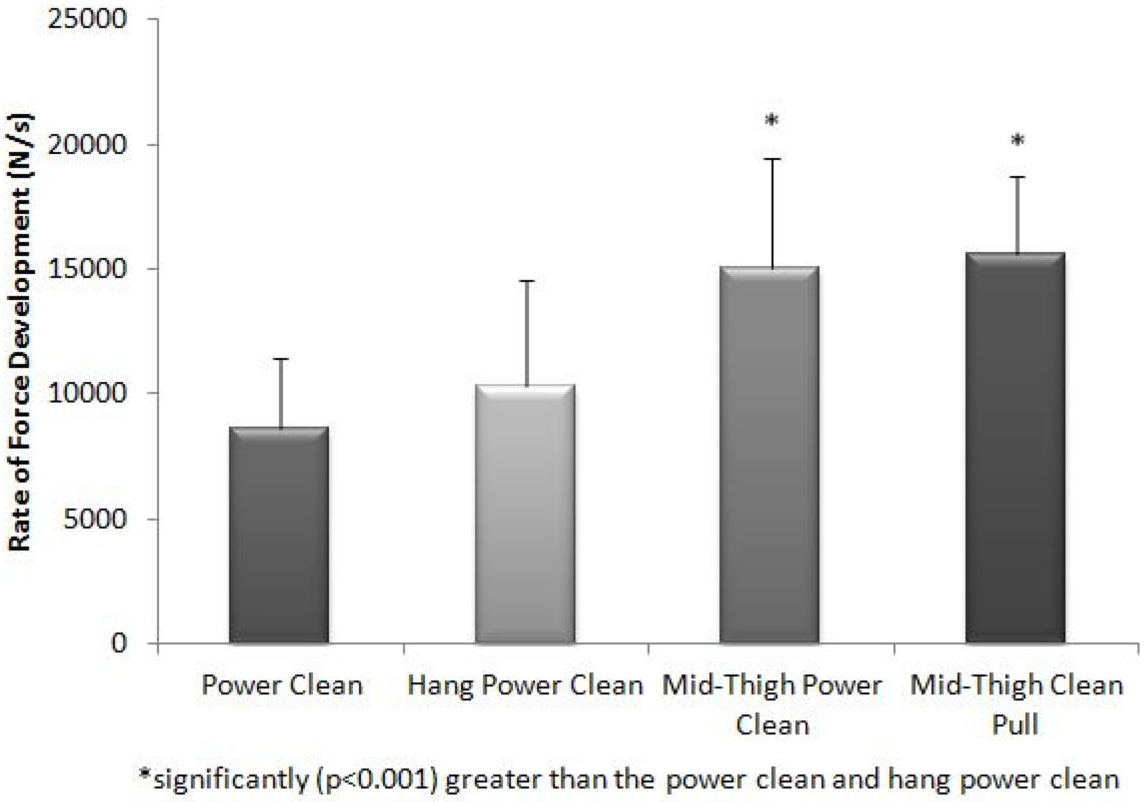

Figure 5.2: Comparison of peak RFD during variations of the power clean

6 Study 3

Kinetic Comparisons during Variations of the Power Clean

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Abstract

The aim of this investigation was to determine the differences in peak power, peak vertical ground reaction forces and rate of force development during variations of the power clean. Elite rugby league players (n=16; age 22.0 ± 1.58 yrs; height 182.25 ± 2.81 cm; body mass 98.65 ± 7.52 kg) performed 1 set of 3 repetitions of the power clean, hang power clean, mid-thigh power clean or mid-thigh clean pull, using 60% of 1 repetition maximum power clean, in a randomized order, while standing on a force platform. One way analysis of variance with Bonferroni post hoc analysis revealed a significantly ($p<0.001$) greater peak power output during the mid-thigh power clean (3565.7 ± 410.6 W) and the mid-thigh clean pull (3686.8 ± 386.5 W) compared to both the power clean (2591.2 ± 645.5 W) and the hang power clean (3183.6 ± 309.1 W), along with a significantly ($p<0.001$) greater peak Fz during the mid-thigh power clean (2813.8 ± 200.5 N) and the mid-thigh clean pull (2901.3 ± 226.1 N) compared to both the power clean (2264.1 ± 199.6 N) and the hang power clean (2479.3 ± 267.6 N). The mid-thigh power clean (15049.8 ± 4415.7 $N.s^{-1}$) and the mid-thigh clean pull (15623.6 ± 3114.4 $N.s^{-1}$) also demonstrated significantly ($p<0.001$) greater instantaneous RFD when compared to both the power clean (8657.9 ± 2746.6 $N.s^{-1}$) and the hang power clean (10314.4 ± 4238.2 $N.s^{-1}$). From the findings of this study, when training to maximize power, Fz and RFD the mid-thigh power clean and mid-thigh clean pull appear to be the most advantageous variations of the power clean to perform.

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6.1 Study 3 Commentary

This was a logical progression from study two, which developed on previously published work of investigating the force and RFD during the power clean, clean and clean pull (Enoka, 1979; Hakkinen et al., 1984; Souza et al., 2002). This study replicated the findings of study two, demonstrating significantly ($p<0.001$) greater peak force and RFD occurs during the mid-thigh power clean and MTCP, when compared to the hang power clean and power clean. Moreover, this study demonstrated that the mid-thigh power clean and MTCP also results in significantly ($p<0.001$) greater peak power when compared to the hang power clean and power clean, with no significant differences ($p>0.05$) between the mid-thigh variations. The higher peak power during the mid-thigh variations is attributable to the higher forces, which are applied over a shorter duration, resulting in a greater acceleration of system centre of mass. When the higher forces multiplied by the corresponding velocity of the system centre of mass the result is a higher peak power.

6.2 Erratum

Study three contains an error in the force values presented in the results section:

‘No significant ($p>0.05$) differences were found when comparing the peak Fz between the mid thigh power clean (2813.82±200.5 N) and the mid thigh clean pull (2901.3±226.1 N). There were no significant differences in peak Fz between the hang power clean (2479.3±267.8 N) and the power clean (2264.1±199.6 N) (Figure 1).’

This should be:

No significant ($p>0.05$) differences were found when comparing the peak Fz between the mid thigh power clean (2801.7±195.4 N) and the mid thigh clean pull (2880.2±236.2 N). There were no significant differences in peak Fz between the hang power clean (2442.9±293.2 N) and the power clean (2306.2±240.5 N) (Figure 1).

This amendment does not alter the differences observed between variations of the power clean, or the resultant levels of significance as determined by the one way analysis of variance.

The same error, with the force data, is also present within the discussion section:

‘Results also showed greater peak Fz during the mid-thigh power clean (2801.7±195.4 N) and the mid-thigh clean pull (2880.2±236.2 N) compared to both the power clean (2306.2±240.5 N) and the hang power clean (2442.9±293.2 N). These values are in line with previous research…’

‘Results showed greater peak Fz during mid thigh power clean (2813.82±200.5 N) and the mid thigh clean pull (2901.3±226.1 N) compared to the power clean (2264.1±199.6 N) and the hang power clean (2479.3±267.8 N). These values are in line with previous research…’

The Fz data presented in figure 1 and in the abstract is correct. All other data (peak RFD and peak power) is also correct.

7 Study 4

No Kinetic Differences during Variations of the Power Clean in Inexperienced Female Collegiate Athletes

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Abstract

Previous research has identified that the second pull phase of the clean generates the greatest power output and that the mid-thigh variations of the power clean also result in the greatest force and power output in male athletes, however, no research has compared the kinetics of the variations of the power clean in females. The aim of this investigation was to identify any differences between variations of the clean, across a range of loads, in inexperienced female collegiate athletes. Sixteen healthy female collegiate athletes (age 19 ± 2.3 yrs; height 166.5 ± 3.22 cm; body mass 62.25 ± 4.52 kg; 1RM power clean 51.5 ± 2.65 kg) performed three repetitions of three variations (power clean, hang power clean, mid-thigh power clean) of the power clean at 60%, 70% and 80% of their predetermined one repetition maximum (1RM) power clean, in a randomized and counter-balanced order. A two way analysis of variance (3x3; load x variation) revealed no significant differences ($p>0.05$) in peak power, peak force (Fz) or rate of force development (RFD) between loads or variations of the power clean. There appears to be no advantage in terms of peak power, Fz or RFD between variations of the clean, in inexperienced female athletes, it is suggested, therefore, that inexperienced athletes intermittently perform different variations of the clean to ensure all round development and technical competence.

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7.1 Study 4 Commentary

While the range of loads (60, 70 80% 1RM power clean) may initially appear to result in a notable difference in loads, and is in line with loading parameters in previous studies, in reality this resulted in a mean barbell mass of 30.9 kg, 36.0 kg and 41.2 kg, respectively. With such small changes in barbell mass (~5 kg), and a change in system mass of ~5% it is not surprising that the differences in kinetic variables between loads was not statistically significant.

8 Study 5

Determination of Optimal Loading during the Power Clean, in Collegiate Athletes

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Abstract

Although previous research has been performed in similar areas of study, the optimal load for the development of peak power during training remains controversial, and this has yet to be established in collegiate level athletes. The purpose of this study was to determine the optimal load to achieve peak power output during the power clean in collegiate athletes. Nineteen male collegiate athletes (age 21.5 ± 1.4 years; height 173.86 ± 7.98 cm; body mass 78.85 ± 8.67 kg) performed three repetitions of power cleans, while standing on a force platform, using loads of 30, 40, 50, 60, 70 and 80% of their pre-determined 1RM power clean, in a randomised, counter-balanced order. Peak power output occurred at 70% 1RM (2951.7 ± 931.71 W), which was significantly greater than the 30% (2149.5 ± 406.98 W, p=0.007), 40% (2201.0 ± 438.82 W, p=0.04) and 50% (2231.1 ± 501.09 W, p=0.05) conditions, although not significantly different when compared to the 60% and 80% 1RM loads. In addition force increased with an increase in load, and peak force occurred at 80% 1RM (1939.1 ± 320.97 N), which was significantly greater (p<0.001) than the 30, 40, 50 and 60% 1RM loads, but not significantly greater (p>0.05) than the 70% 1RM load (1921.2 ± 345.16 N). In contrast there was no significant difference (p>0.05) in rate of force development across loads. When training to maximise force and power it may be advantageous to use loads equivalent to 70-80% of 1RM in an attempt to maximise training adaptations and athletic performance.

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8.1 Study 5 Commentary

The findings of this study were in line with hypotheses and previous research, demonstrating that peak power output occurs at 70% 1-RM power clean, although this was not significantly ($p>0.05$) different to loads ±10% of the load that elicited peak power (Kawamori and Haff, 2004; Haff et al., 2005; Kawamori et al., 2005; Cormie et al., 2007c; Cormie et al., 2007e; Kilduff et al., 2007).

9 Study 6

The Effect of Loading on Kinematic and Kinetic Variables during the Mid-Thigh Clean Pull

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Abstract

The ability to develop high levels of muscular power is considered a fundamental component for many different sporting activities; however the load that elicits peak power still remains controversial. The aim of the current study was to determine at which load peak power output occurs during the mid-thigh clean pull. Sixteen participants (Age 21.5 ± 2.4 years; height 173.86 ± 7.98 cm; body mass 70.85 ± 11.67 Kg) performed mid-thigh clean pulls at intensities of 40, 60, 80, 100, 120 and 140% of 1 repetition maximum (1RM) power clean in a randomised and balanced order using a FT700 ballistic measurement system incorporating a force plate and linear position transducer to assess velocity, displacement, peak power, peak force (Fz) and rate of force development (RFD). Intra-class correlations for each dependant variable demonstrated high reliability ($r \geq 0.935$, $p<0.001$), at each intensity; although RFD, showed only a moderate reliability ($r=0.619$, $p=0.012$). Significantly greater Fz occurred at a load of 140% (2778.65 ± 151.58 N, $p<0.001$), RFD at a load of 120% (26224.23 ± 2461.61 $N.s^{-1}$, $p=0.004$), where as peak velocity (1.693 ± 0.042 $m.s^{-1}$, $p<0.001$) and peak power (3712.82 ± 254.38 W, $p<0.001$) occurred at 40% 1RM. The results indicate that increased loading results in significant ($p<0.001$) decreases in peak power and peak velocity during the mid-thigh clean pull; below peak values obtained at an intensity of 40% 1RM. Moreover, if maximising force production is the goal then training at a higher load may be advantageous, with peak Fz occurring at 140% 1RM.

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9.1 Study 6 Commentary

This study was a progression from studies 2 and 3 to investigate the effect of loading on force time characteristics during the MTCP. As studies 2 and 3 showed no significant differences in kinetic variables between the MTCP and the mid-thigh power clean, the MTCP was selected as it permits loads >100% 1RM power clean, therefore allowing a greater range of loads to be studied.

During the initial submission of the manuscript RFD measures included peak RFD, mean RFD and mean RFD from 0-100 ms, 0-200 ms and 0-250 ms, however, only peak RFD was reliable (ICC ≥ 0.80) within session. This is in line with recent findings by Haff et al. (2015) who reported that peak RFD was the most reliable measure of RFD during the isometric MTCP. The reviewers, therefore, recommended that only peak RFD was reported and the other RFD variables deleted from the manuscript. A further suggestion, from the reviewers, was to look at impulse across different time frames, as included in the final manuscript, as these variables demonstrated good within session reliability.

DISCUSSION

10 DISCUSSION

Numerous variations of the power clean are regularly incorporated into the strength and conditioning programmes of athletes, however, there is a distinct lack of evidence to inform strength and conditioning coaches on the potential benefits of the primary power clean variations. The aims of this series of investigations was to compare the kinetic variables (peak force, peak rate of force development (RFD) and peak power) during selected variations of the power clean (power clean, hang power clean, mid-thigh power clean and mid-thigh clean pull (MTCP)), to identify which of these variations are optimal for the development of force time characteristics. An additional aim was to determine if load has the same effect on kinetic variables, during the power clean, as previously reported in well trained athletes, in inexperienced athletes. A further aim was to identify which loads optimise the different force time characteristics, during the preferred power clean variation (MTCP - as identified in studies 2 and 3), to help to fully inform strength and conditioning practitioners when selecting appropriate variations of the power clean and to inform the process of selecting the appropriate loads to elicit the desired force time characteristics during training.

The reliability study (Study 1) highlighted that, in line with hypothesis 1, all kinetic variables are highly reliable both within (ICC ≥0.969) and between sessions (ICC ≥0.988). Subsequent findings demonstrated that the MTCP and mid-thigh power clean are preferential in terms of acutely maximising kinetic performances when compared to the other derivatives of the power clean (power clean and hang power clean), as they result in the greatest peak force, peak RFD and peak power (Study 2 & 3), in line with hypotheses 2 and 3. These findings are comparable to previous observations of Olympic lifters which revealed that the second pull phase of the clean results in the greatest force (Enoka, 1979; Hakkinen et al., 1984;

Garhammer and Gregor, 1992; Souza et al., 2002) and power (Garhammer, 1979, 1980, 1982, 1985). As previously mentioned however, by the time the second pull commences the bar has already gained momentum, therefore it is unsurprising that the highest power output occurs during this phase, especially if assessed via bar velocity. Interestingly, even though the bar has already gained momentum, peak force has also been observed to occur during the second pull phase of the clean and clean pull (Enoka, 1979; Hakkinen et al., 1984; Garhammer and Gregor, 1992; Souza et al., 2002), although until studies 2, 3 and 4, no previous research had compared the effect of the different start positions (from the floor, knee and mid-thigh), on kinetic variables, during the power clean variations.

The higher peak force observed during the mid-thigh variations, is likely a result of the individuals intent to accelerate the bar and the reduced time to apply force and displace the bar from mid-thigh when compared to the other start positions (from the floor and from the knees). The greater force production, combined with the reduced duration to apply force, is the likely result of the greater peak RFD observed in when the lifts are performed from mid-thigh. Moreover, the greater force applied at a higher rate (increased RFD) to the mass of the system would result in an increased impulse and therefore acceleration of the system COM, as explained by Newton's second law (F=MA). The greater acceleration of the system COM would therefore result in a higher peak velocity of system COM, resulting in the higher peak power outputs observed from the mid-thigh position.

Our findings have been further supported by Suchomel et al. (2014c), who compared kinetic variables (peak force, peak power and peak velocity of system COM) during the jump shrug, hang power clean and high pull, performed at different loads (30, 45, 60 and 80% 1-RM hang power clean). Their study demonstrated the greatest peak power and velocity of system COM occurred during the jump shrug, when performed at 30% 1-RM, compared to the hang power clean and high pulls and compared to other loads, with a progressive increase in peak force as loading increased.

In contrast to the previously mentioned findings in well trained males (Studies 2 and 3), it was observed that changing load and power clean variations resulted in no kinetic differences in inexperienced female collegiate athletes (Study 4); contrary to hypothesis 4. As the mid-thigh power clean is the least technical variation of the power clean, when compared to the power clean and hang power clean, a greater difference between variations was expected, with the MTCP expected to demonstrate the greatest values in the kinetic variables compared to the hang power clean and power clean, irrespective of load, based on the findings of studies 2 and 3. The absence of significant differences in kinetic variables, between loads, is likely to be attributable to small absolute changes in barbell mass (~5 kg), resulting in a change in system mass of ~5%. While the range of loads (60, 70 80% 1RM power clean) may initially appear to result in a notable difference between loads, and is in line with loading parameters in previous studies (Kawamori and Haff, 2004; Kawamori et al., 2005; Cormie et al., 2007d; Cormie et al., 2007e; Kilduff et al., 2007), in reality this resulted in a mean barbell mass of 30.9 kg, 36.0 kg and 41.2 kg, respectively.

Based on the findings of study 4, it is suggested that loads of 60-80% 1-RM power clean can be used interchangeably, in inexperienced female athletes, without a resultant decrease in kinetic values. It is therefore recommended that loading be adopted in a linear periodized approach, starting with the lighter loads and gradually progressing to the heavier loads as technique improves. Moreover, as the study showed no difference in kinetics between variations of the power clean, in inexperienced female athletes, it may be beneficial to alter the variation of the lift performed during each training session, so that athletes' develop competency in each variation of the lift and reduce monotony within the athletes' training programme.

As hypothesised, study 5 revealed that peak power output was achieved at a load of 70% 1-RM, although this was not significantly ($p>0.05$) different when compared to the 60% and 80% 1-RM loading conditions, in inexperienced athletes. These findings are in line with results of previous research investigating the effects of loading, during the power clean, in well trained athletes where no significant ($p>0.05$) differences were observed ±10% of the load that elicited the greatest peak power (Cormie et al., 2007c; Cormie et al., 2007d). It may be beneficial, therefore, to progressively increase loading from 60-80% 1-RM as the athletes experience level and competence increases. The lighter loads may allow the athlete to focus more on ensuring appropriate technique, rather than focussing on lifting the load, therefore enhancing technical competency, without noticeably reducing the force time characteristics during the lift, which will be highly beneficial in athletes inexperienced in performing these exercises.

Importantly, the MTCP eliminates the catch phase of the power clean, therefore permitting the use of loads >100% 1-RM power clean. When loads of 120-140% 1-RM power clean are used, during the MTCP significantly, greater peak force, peak RFD and impulse occur when compared to loads ≤100% 1-RM power clean (Study 6), in line with hypothesis 7. These increases in peak force and RFD, observed with an increase in load, are in line with previous studies identifying the effect of loading on the power clean (Cormie et al., 2007c; Cormie et al., 2007e), hang power clean (Kawamori et al., 2005; Kilduff et al., 2007) and the MTCP (Kawamori et al., 2006), although none of these studies used loads as high as in the present study. Only Kawamori et al. (2006) used loads above 90% 1-RM, although they stopped at 120% 1-RM. Previous research has also demonstrated similar trends in terms of peak RFD, with a progressive increase in peak RFD with an increase in load during the hang power clean (Kawamori et al., 2005; Kilduff et al., 2007). In contrast however, Kawamori et al. (2006) reported a progressive, although non-significant ($p>0.05$) decline in peak RFD as load increased.

In contrast to the increase in peak force and peak RFD with an increase in load, during the MTCP (Study 6), peak power, bar displacement and bar velocity demonstrated a progressive decline as load increased. Peak power, bar displacement and bar velocity occurred at loads of 40-60% 1-RM power clean, as hypothesised, although <40% 1-RM was not assessed. In line with our findings, Suchomel et al. (2013) recently investigated the effects of loading during the jump shrug exercise, reporting that 30% 1-RM hang power clean resulted in the greatest velocity of COM and peak power, compared to loads of 45, 65, 80% 1-RM. The kinematics of the jump shrug is similar to the MTCP in terms of the concentric phase; although the authors had the subjects initiate the activity with a countermovement, with the obvious difference being that the subjects leave the ground at the end of the concentric phase during the jump shrug. Irrespective of this variation in technique, the greatest peak power was achieved at the lowest load, similar to Study 6 and previous research using the MTCP (Kawamori et al., 2006) and squat jump (Stone et al., 2003a; Cormie et al., 2007a; Cormie et al., 2007c; Cormie et al., 2007b; Cormie et al., 2007e; Cormie et al., 2008; McBride et al., 2011). The potential benefits of using a low load to elicit peak power is important as it highlights that athletes do not always need to use near maximal loads in order to enhance their athletic development; further highlighting the importance of the intention to move quickly (Behm and Sale, 1993). Such strategies may be beneficial in aiding in injury risk reduction and the reduction of total work volume during tapering, or periods of intensive competition when training volumes may need to be reduced to facilitate recovery between competitions, although maintenance of force production is essential.

The fact that peak bar velocity shows comparable trends to peak power output, with a progressive decline as load increased, is extremely valuable, as strength and conditioning coaches that do not have access to force plates could potentially use bar velocity to identify the optimal loads, and occurrence of fatigue during training when using the MTCP. While it is acknowledged that there are issues with assessing power output using bar velocity, using inverse dynamics (Cormie et al., 2007a; Cormie et al., 2007c; Cormie et al., 2008; McBride et al., 2011; Lake et al., 2012), as discussed in detail in Chapter 3.1, the use of linear position transducers, in an applied setting, can provide rapid feedback to the coach and athlete regarding performance during a training session. In such a situation the focus should be on bar velocity, rather than calculating power output from bar velocity (inverse dynamics), to identify fatigue (terminating a set once bar velocity decreases >10% (Baker and Newton, 2007)), or optimal loading. Identifying fatigue during each set of an exercise is important when using loads that differ from the usual high loads recommended for training power as, Thomasson and Comfort (2012) and Comfort et al. (2013a) identified that a greater number of repetitions (~10 repetitions) can be performed, than normally recommended ≤6 repetitions (Stone et al., 2007; Baechle et al., 2008; Cormie et al., 2011b; Haff and Nimphius, 2012), when using the load that elicits peak power output (body mass, no external load) and loads

≤40% 1-RM, during the squat jump. It should be acknowledged, that in such situations, the strength and conditioning coach should provide appropriate coaching and feedback to ensure that the athlete does not increase bar velocity via changing their technique (e.g. excessive elbow flexion during the MTCP).

Importantly, the significant differences ($p<0.05$) observed between the variations of the power clean (Study 2 & 3), between loads of the power clean (Study 5) and between loads during the mid-thigh clean pull (Study 6) were all greater that than the SDD's reported in study 1. The magnitudes of these differences, therefore, highlight a meaningful difference in kinetic variables between exercises and loads. It should be acknowledged, however, that these SDD's were extremely low and may be due to the fact that strict controls were put in place during each testing session and between testing sessions; including visual analysis of force time curves to ensure that the force traces were representative of a power clean. For calculation of peak power output, using forward dynamics, it was essential that the force time data represented a stable system mass prior to commencement of the lift, furthermore it was essential that two clear peaks occurred, during the concentric phase of the lift, illustrating the first pull and second pull respectively. Any trials that did not meet these criteria were discounted and repeated after an appropriate rest period. Such strict criteria improve the scientific rigour of data collection procedures, but may actually reduce ecological validity; as such strict controls are unlikely to be used in a real world environment, especially when working in team sports with large numbers of athletes. It is likely that the implementation of such criteria dramatically improved the reliability and therefore resulted in such small SDD's for each variable.

It should be noted, however, that the other variations of the power clean do have their advantages, and should be used accordingly. In general, the power clean permits athletes to uses heavier loads than the other versions of the power clean (mid-thigh power clean and hang power clean). This is because the bar is displaced further during the power clean, permitting additional time for force to be applied to the bar, which results in greater acceleration and therefore greater peak vertical displacement of the bar, which in turn results in a successful catch with a higher load (Kelly et al., 2014). The hang power clean, begins with a countermovement where the knees slide back under the bar (also referred to as the ‘double knee bend’, ‘scoop’ or ‘transition’), which is suggested to train the stretch shorten cycle (SSC) (Enoka, 1979; Isaka et al., 1996), although more research is required to substantiate this claim. If the SSC is stimulated it would be feasible to expect that the power output would be greater than during the mid-thigh versions of the exercise, however, greater peak force, peak RFD and peak power were not observed during our studies. The transition phase, therefore, warrants further research to determine if the SSC is effectively trained using the hang power clean. In addition, both the power clean and the clean incorporate the transition phase and also exhibit a force time curve which represents an unweighting phase similar to that of a countermovement jump (Garhammer, 1980; Garhammer, 1985; Garhammer and Gregor, 1992), therefore it would be beneficial to determine if the SSC is appropriately stimulated during the power clean and clean.

In proficient lifters, the clean (sometimes referred to as the squat clean), also permits a higher load to be lifted when compared to the power clean variations; due to the greater squat depth during the catch the bar does not have to be displaced as far as when compared to the power clean. The catch phase of the clean may be useful in training general athleticism, as it relies on a rapid transition from rapid high force concentric muscle action (pull phase) which takes

0.66-0.76 s (Garhammer, 1985), to rapid lengthening of the muscles (rapid descent phase) lasting 0.32-0.38 s (Garhammer, 1985), followed by a rapid isometric muscle action (catch phase). Similar qualities, however, may be trained through a variety of plyometric tasks, albeit without such external loads.

10.1 Practical Application

When incorporating the MTCP into different training mesocycles, it would be useful to use heavier loads during the strength phases, progressing from 120-140% 1-RM power clean, or possibly higher loads, to maximise peak force production and peak RFD. Based on the size principle, such high loads are also likely to recruit high threshold motor units (Henneman et al., 1974; Schmidtbleicher and Haralambie, 1981; Sale, 1987; Henneman, 1991) and are therefore likely to enhance the development of both force and RFD (Wilson et al., 1993; McBride et al., 2002; Harris et al., 2008). In contrast, during power mesocycles, it would be advantageous to progressively reduce load to 40-60% 1-RM power clean, to elicit the greatest movement velocity and peak power, during either the MTCP or mid-thigh power clean. Strength and conditioning coaches should note, however, that some lower load, higher velocity movements should be included during the strength mesocycles, and some high load activities should be included during the power mesocycles to ensure that movement velocity and maximal force production, respectively, are maintained (Newton and Kraemer, 1994; Newton et al., 2002; Cormie et al., 2011b; Haff and Nimphius, 2012). This combined approach, with an emphasis on either movement velocity or force production, although not at the expense of the other, appears to be the most productive approach to maximising power output (Kaneko et al., 1983; Wilson et al., 1993; Toji et al., 1997; Toji and Kaneko, 2004; Cormie et al., 2011b; Haff and Nimphius, 2012).

The findings of this series of studies clearly illustrates that while the power clean is beneficial in terms of developing athleticism it is not essential that the catch phase be used when aiming to maximise peak force, peak RFD and peak power. Athletes could rely on the MTCP, which also permits the use of higher loads (>100% 1-RM) during strength mesocycles. These findings have recently been confirmed for other power clean derivatives, namely the jump shrug and hang high pull (Suchomel et al., 2013; Suchomel et al., 2014a; Suchomel et al., 2014b; Suchomel et al., 2014c). Additionally, along with such strategies now being incorporated in to athletes' training programmes, published reviews are also recommended similar applications of these findings to maximise force time characteristics during athletes training programmes (DeWeese and Scruggs, 2012; DeWeese et al., 2013; Suchomel and Sato, 2013).

10.2 Ongoing Research

10.2.1 Citations

These combined publications have been cited >60 times (Table 10.1) and influenced the publication of a series of other related publications (See section 10.2.2 Impact in the field)

Table 10.1 Citations for each publication

Publication	**Number of Citations** (Google Scholar 18/01/15)
Comfort, P, Allen, M, and Graham-Smith, P. Comparisons of peak ground reaction force and rate of force development during variations of the power clean. J Strength Cond Res 25 (5): 1235-1239, 2011	23
Comfort, P, Allen, M, and Graham-Smith, P. Kinetic comparisons during variations of the power clean. J Strength Cond Res 25 (12): 3269–3273, 2011	18
Comfort, P, Fletcher, C, and McMahon, JJ. Determination of optimal loading during the power clean, in collegiate athletes. J Strength Cond Res 26 (11): 2970–2974, 2012	12
Comfort, P, Udall, R, and Jones, PA. The effect of loading on kinematic and kinetic variables during the mid-thigh clean pull. J Strength Cond Res 26 (5): 1208–1214, 2012	8
Comfort, P. Within-and between-session reliability of power, force, and rate of force development during the power clean. J Strength Cond Res 27 (5): 1210–1214, 2013	4
Comfort, P, McMahon, JJ, and Fletcher, C. No kinetic differences during variations of the power clean in inexperienced female collegiate athletes. J Strength Cond Res 27 (2): 363–368, 2013	1

10.2.2 Influence in the field

Since the publication of the studies within this thesis three additional related studies have been published developing this theme of research, by Suchomel and colleagues based at East Tennessee State University, which support our observations:

- Suchomel, T.J., Beckham, G.K. and Wright, G.A. (2014). The Impact of Load on Lower Body Performance Variables during the Hang Power Clean. Sports Biomechanics, 13(1), 87-95.
- Suchomel, T.J., Wright, G.A., Kernozek, T.W. and Kline, D.E. (2014). Kinetic Comparison of the Power Development between Power Clean Variations. The Journal of Strength & Conditioning Research, 28 (2): 350-360.
- Suchomel, T.J., Beckham, G.K. and Wright, G.A. (2013). Lower Body Kinetics During the Jump Shrug: Impact of Load. Journal of Trainology, 2: 19-22.

In addition, these studies have been cited by a number of published reviews relating to coaching the Olympic lifts and their derivatives, development of strength and power and the rehabilitation of injured athletes:

- Maloney, S.J., Turner, A.N. and Fletcher, I.M. (2014). Ballistic Exercise as a Pre-Activation Stimulus: A Review of the Literature and Practical Applications. Sports Medicine. E-pub ahead of print.
- Suchomel, T.J., DeWeese, B.H., Beckham, G.K., Serrano, A.J. and Sole, C.J. (2014). The Jump Shrug: A Progressive Exercise into Weightlifting Derivatives. Strength & Conditioning Journal, 36 (3): 43-47
- Suchomel, T.J. and Sato, K. (2013). Baseball Resistance Training: Should Power Clean Variations Be Incorporated? Journal of Athletic Enhancement., 2 (2).
- DeWeese, B.H., Serrano, A.J., Scruggs, S.K. and Burton, J.D. (2013). The Mid-thigh Pull: Proper Application and Progressions of a Weightlifting Movement Derivative. Strength & Conditioning Journal, 35 (6): 54-58.

- VanGelder, L.H., Hoogenboom, B.J. and Vaughn, D.W. (2013). A Phased Rehabilitation Protocol for Athletes with Lumbar Intervertebral Disc Herniation. Int J Sports Phys Ther, 8 (4): 482-516.

Our own research is still progressing in these areas, with articles in press or currently under review, including some external collaboration:

- Comfort, P., Mather, D. and Graham-Smith, P. (2013). No Differences in Kinetics between the Squat Jump, Push Press and Mid-Thigh Power Clean. Journal of Athletic Enhancement. 2(6).
- Comfort, P., Jones, P.A., McMahon, J.J. and Newton, R. (2015). Effect of Knee and Trunk Angle on Kinetic Variables during the Isometric Mid-Thigh Pull: Test-Retest Reliability. Int J Sports Physiol Perform. **10 (1): 58-63**
- Lake, J.P., Mundy, P.D. and Comfort, P. (2014). Power and Impulse Applied During Push Press Exercise. J Strength Cond Res. 28 (9): 2552-2559.
- Suchomel, T. J., Comfort, P. & Stone, M. H. Weightlifting Derivatives: rationale for Implementation and Application. Sports Medicine. **In Press**
- Comfort, P. Jones, P. A. And Udall, R. The Effect of Load and Sex on Kinetic and Kinematic Variables during the Mid-Thigh Clean Pull. Sports Biomechanics. **In press**
- Comfort, P. Mundy, P. D., Graham-Smith, P., Jones, P. A., Smith, L. C. And Lake, J. P. Comparison of Peak Power Output during Exercises with Similar Lower-limb Kinematics. Sports Biomechanics. **Under review**

In addition to the published reviews recommending similar applications of the findings of this thesis (DeWeese and Scruggs, 2012; DeWeese et al., 2013; Suchomel and Sato, 2013), these findings are being applied in athletes training programmes.

10.3 Limitations

Very small SDD values observed during study 1 may be due to the fact that strict controls were put in place during each testing session and between testing sessions, including visual analysis of force time curves to ensure that the force traces were representative of a power clean. In order to calculate peak power, using a forward dynamics approach, it was essential that the force time data represented stable system mass prior to commencement of the lift. In addition, the criteria to determine a 'good performance' was visual observation of the lift and visual inspection of the force time curve which was required to show two clear peaks occurred during the concentric phase of the lift, illustrating the first pull and second pull respectively. Any trials that did not meet these criteria were discounted and repeated after an appropriate rest period. Such strict criteria improve the scientific rigour of data collection procedures, but actually reduce ecological validity as such strict controls are unlikely to be used in a real world environment, especially when working in team sports with large numbers of athletes. It is likely that the implementation of such criteria dramatically improved the reliability and therefore resulted in such small SDD values for each variable.

Studies 2-3 only used a load of 60% 1-RM power clean, which may slightly bias the results towards the MTCP, as research by Kawamori et al. (2006) showed that peak power occurred in this loading conditioning, although this was not significantly different ($p>0.05$) to peak power output at 30, 90 and 120% 1-RM power clean. In contrast, peak force progressively and significantly ($p<0.05$) increased with load with the greatest force produced at 120% 1-RM, similar to our findings in Study 6. Cormie et al. (2007c; , 2007e) reported that peak power in the power clean occurred at 80% 1-RM, whereas Kawamori et al. (2005) and Kilduff et al. (2007) reported that peak power in the hang power clean occurred at 70% and 80% 1-RM, respectively. It is worth noting that there were no significant differences ($p>0.05$) in peak power output between loads of 50-90% 1-RM in any of these studies, therefore any bias towards the MTCP should be minimal, and based on the results of the aforementioned studies, non-significant. In addition, Study 4 demonstrated no significant differences in kinetic variables, based on load (60, 70, 80% 1-RM power clean) or variation of the clean, albeit in female athletes who were inexperienced in performing the power clean.

Furthermore, it could be argued that when comparing the power clean, hang power clean and mid-thigh power clean, the loads used for each variation should be relative to the 1-RM for that specific variations. This approach was not used however, as this would have resulted in different loads for each variation of the clean and therefore it would not have been possible to identify if any differences in kinetic variables was due to power clean variation or load, whereas with a standardised load only the exercise variation could affect the kinetic variables. More recently, we have demonstrated that 1-RM power clean performance, does indeed result in a higher load lifted compared to the hang power clean (performed from the knee) (6.63%) and the mid-thigh power clean (7.35%) (Kelly et al., 2014). As previous research has shown no differences in kinetic variables ±10% of the optimal load (Kawamori and Haff, 2004; Kawamori et al., 2005; Kawamori et al., 2006; Cormie et al., 2007c; Cormie et al., 2007e; Hori et al., 2007; Kilduff et al., 2007; McBride et al., 2011), such differences (<10%) in loading are unlikely to significantly affect the kinetics during these lifts. The approach used also increased ecological validity, as most strength and conditioning coaches would usually select training loads for these exercises based on either a 1-RM power clean or hang power clean and would be unlikely independently assess 1-RM performance in each variation of the power clean.

Studies 1-5 also relied on subjects holding the load off the floor for one second, prior to commencing the exercise, which will slightly reduce ecological validity, as the load would usually start on the floor during the power clean. However, to ensure that the conditions were comparable between variations of the power clean it was essential that the subjects were already under tension during the power clean, as this is how the MTCP, mid-thigh power clean and hang power clean begin. More importantly, it is also essential that the system mass is applied to the force plate, prior to the commencement of the activity, to permit calculation of velocity of system centre of mass and therefore power using forward dynamics (Cormie et al., 2007a; Cormie et al., 2007c; Cormie et al., 2007b; Cormie et al., 2007e; Hori et al., 2007).

While Study 4 showed no significant differences (p>0.05) in kinetic variables, between load or power clean variation, in inexperienced female collegiate athletes, these differences were greater than the SDD's reported both within and between session for the power clean (Study 1). It must be noted, however, that the resultant SDD's in Study 1 were for the power clean only and used well trained rugby league players. The absence of significant differences in kinetic variables, between loads, is likelt to be attributable to small absolute changes in barbell mass (~5 kg), resulting in a change in system mass of ~5%. Future research, therefore, should examine a greater range of loads using increments of 15% 1RM.

These studies have identified the acute kinetic advantages of the use of the mid-thigh power clean and MTCP, the potential chronic benefits and adaptations to such training modalities, using an intervention study, have not been investigated. It is likely that a greater adaptive response would be likely to occur from to performing the mid-thigh power clean and MTCP, compared to the power clean and hang power clean, due to the higher kinetic values during the mid-thigh power clean and MTCP. In addition performing the MTCP at higher loads (120-140% 1RM) is also likely to result in greater increases in peak force and peak RFD compared to the other variations of the power clean due to the ability to use higher loads (>100% 1RM) which acutely result in the greatest peak force and peak RFD. Based on the size principle, such loads are likely to recruit high threshold motor units (Henneman et al., 1974; Schmidtbleicher and Haralambie, 1981; Sale, 1987; Henneman, 1991), especially when the intention is to move as quickly as possible (Behm and Sale, 1993) and are therefore likely to enhance both force and rate of force development (Wilson et al., 1993; McBride et al., 2002; Harris et al., 2008). Future studies need to determine if the chronic use of such clean variations and loading parameters results in a greater adaptive response in terms of force time characteristics and architectural changes to lower limb musculature and more importantly athletic performance.

The kinetic observations are likely to be similar in Olympic weightlifters, as they are in line with the trends reported previously in such populations (Enoka, 1979; Garhammer, 1979; Garhammer, 1980; Garhammer, 1982; Hakkinen et al., 1984; Garhammer, 1985; Garhammer, 1991; Garhammer, 1993; Souza et al., 2002). However, a primary focus for Olympic weightlifters is to ensure maximal displacement of the bar, with an appropriate bar path, to permit a successful catch phase with a maximal load, rather than focussing on performing the exercise variation and load that maximises lower body power output. Therefore, while some team sport and individual athletes could, potentially, perform variations of the clean which do not rely on learning to catch the bar in a power clean or full depth position Olympic weightlifters must regularly perform the full lift, or drills to enhance their technique during the catch phase.

While the subject population for each study was homogenous, to meet the assumptions required for parametric testing, which may limit the ability to generalise the findings to other populations, the subjects for each study were different which should enhance the ability to generalise these findings. For example, studies 2 and 3 both used well trained professional rugby league players, although the subjects in each study were different; both studies demonstrated similar trends. Similarly, studies 4 and 5 both used novice collegiate level athletes, and while study 4 used females and 5 used males, both studies demonstrated similar findings, with no significant differences ($p>0.05$) in kinetic variables across loads of 60, 70 and 80% 1-RM power clean. It is also noteworthy that the subjects used in studies 1, 2 and 3 are representative of many team sport athletes in terms of their relative strength levels and training experience, while the subjects used in studies 4, 5 and 6 are representative of collegiate athletes (in the United Kingdom), and as such the findings of these studies should be applicable to both categories of athletes. Further research with better trained (stronger more experienced) athletes, to determine if these trends are consistent in such populations, is suggested.

10.4 Areas of Future Research

The primary aim for the future development of this study area should be to integrate the MTCP into a power training mesocycle to compare if the resultant adaptations are greater when compared to the other variations of the clean. It is suggested that the mid-thigh variations of the power clean will result in greater increases in athletic development compared to the power clean and hang power clean, due to the greater peak force, peak RFD and peak power achieved during the mid-thigh variations of the power clean.

Further comparisons of the kinetics during clean pull variations (clean pull, hang clean pull, MTCP) across a range of loads, progressing to loads ≥140% 1-RM power clean would also add to the developing body of knowledge in this area. It is likely that the trends between the clean pull variations will be similar to the trends observed between power clean variations in this thesis, as the concentric phases are identical. Due to the clean pull variations omitting the catch phase, it would be interesting to see if such trends occur as load increases. Such studies would be beneficial to inform strength and conditioning coaches regarding the effects of exercise variation and loading on specific force time variables, which would help to ensure appropriate evidence based exercise selection.

In addition kinetic comparisons between the power snatch variations (power snatch, hang power snatch, power snatch from the hip) would be advantageous, to determine if the trends are similar to the kinetics during the clean variations described in this thesis. Moreover, comparison of the kinetics during the power clean variations and the power snatch variations would also be useful, to inform strength and conditioning coaches regarding exercise selection and appropriate loading to emphasise peak force, peak RFD and peak power.

As there appear to be no differences in kinetic variables between loads, when using 10% increments (Kawamori and Haff, 2004; Kawamori et al., 2005; Kawamori et al., 2006; Cormie et al., 2007c; Cormie et al., 2007e; Hori et al., 2007; Kilduff et al., 2007; McBride et al., 2011), future research could use increments of 15-20% 1-RM, as recently used by Suchomel et al. (2013, 2014a, 2014c).

Each of the six studies in this thesis began with the participants in a static position and eliminated any initial lowering of the barbell, however, in the recent studies by Suchomel et al. (2013, 2014a, 2014c) participants performed the hang power clean and the jump shrug from an upright position, initiating movement with a countermovement as they lowered the bar to the starting position. It would be useful for future research to identify if the addition or exclusion of this countermovement affects kinetic variables during such exercises, to determine if commencing the activity by starting from a static position, as used in the studies included in this thesis, or by initiation of the SSC, is most beneficial for enhancing force time characteristics and adaptations to training.

Additionally, due to the high reliability ($r \geq 0.988$) and low SDD's ($\leq 2.5\%$) observed during the kinetic assessment of the power clean (Study 1) and the recent findings of Comfort et al. (2014a) which identified similarly high reliability and low SDD's during the IMTP, it would be useful to identify how such measures can be used to identify neuromuscular fatigue and adaptations to training. In addition, comparing whether isometric or dynamic assessments are more closely related to performance in athletic tasks, or to determine their ability to identify neuromuscular fatigue would be useful in applied settings.

10.5 Conclusion

This series of studies has identified that the MTCP and mid-thigh power clean are preferential, when compared to the power clean and hang power clean, when aiming to elicit the greatest peak force, peak RFD and peak power output. When peak power is the primary focus, it would be advantageous to progressively reduce loading to 40-60% 1-RM power clean, to elicit the greatest movement velocity and peak power. As there were no differences in kinetics during the mid-thigh power clean and MTCP, these exercises may be used interchangeably at submaximal loads during power mesocycles. In addition, when aiming to maximise peak force and peak RFD the MTCP would be preferential as loads >100% 1RM can be used, with loads of 120-140% 1-RM power clean, or possibly higher, resulting in the greatest peak force and peak RFD.

Additionally, the lighter loads (40-60% 1-RM power clean) which elicit peak power output, during the MTCP and mid-thigh power clean, may be beneficial for injury risk reduction and the reduction of total work volume during tapering, or periods of intensive competition, when training volumes may need to be reduced to facilitate recovery between competitions, although maintenance of strength is essential.

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11 REFERENCES

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