Can a pre-training biomechanical pathway identify the most effective exercise to enhance a given group's, subgroup's or individual's countermovement jump height?

A thesis submitted for the Degree of Doctor of Philosophy

by

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Declaration

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Abbreviations

COM	whole body centre of mass
BDJ	bounce drop jump
CDJ	countermovement drop jump
CMJ	countermovement jump
DJ	drop jump
JR	joint reversal
PDF	performance determining factor
PRF	performance related factor
RFD	rate of force development
RPD	rate of power development
RMD	rate of moment development
SSC	stretch-shortening cycle
1RM	one repetition maximum

Glossary of Terms

Appropriate training stress
Training stress that would be expected to lead to a post-training enhancement in a given CMJ parameter after a suitable period of training

Biomechanical diagnostic and prescriptive pathway
A proposed biomechanical pathway that may allow a pre-training identification of the most effective exercise to enhance a given group's, subgroup's or individual's countermovement jump ability

Cluster analysis
A form of statistical analysis that establishes homogenous groups of individuals based on scores across a number of variables

Expected training effect
The post-training magnitude change that a given CMJ parameter was expected to undergo following training

Inappropriate training stress
Training stress that would be expected to lead to a post-training decline in a given CMJ parameter after a suitable period of training

Performance related factor
A biomechanical parameter that is significantly acutely correlated with performance outcome

Performance determining factor
A biomechanical parameter whose post-training magnitude change is significantly correlated with a post-training change in performance outcome

Pre-training stress analysis
An acute pre-training identification of the training stress (overload) that given CMJ parameters experience in a training exercise of interest

Single-subject analysis
A form of statistical analysis that involves analysing repeat performances from one individual

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Abstract

Author: Brendan Marshall

Title: Can a pre-training biomechanical pathway identify the most effective exercise to enhance a given group's, subgroup's or individual's countermovement jump height?

Background: Countermovement jump (CMJ) ability is an important contributor to successful performance in many sports. While the drop jump, squat, jump squat and power clean training exercises are each purported to enhance maximal CMJ jump height, there are generally inconsistent findings regarding their effectiveness at doing so. The resounding implication of this is that a coach cannot be sure as to which training exercise will be most effective at enhancing their athletes' CMJ jump height. In an attempt to address this issue a biomechanical diagnostic and prescriptive pathway has been proposed that may allow the pre-training identification of the most effective exercise to enhance a given group's, subgroup's or individual's CMJ jump height. The current study aims to test the efficacy of the proposed pathway with a single acute research study and two training studies.

Methods: All three studies required a kinetic and kinematic analysis of the CMJ and each training exercise under examination (study 1: drop jump, jump squat, squat and power clean; study 2: low amplitude drop jump; study 3: larger amplitude drop jump). From ground reaction force and motion data, kinetic, kinematic and coordination parameters were calculated at the whole body, hip, knee and ankle. Correlation analysis was used to identify CMJ performance related factors (PRFs) while tests of statistical difference were used to identify the acute training stress experienced by CMJ PRFs.

Findings: Study one indicated that the proposed pathway may provide a means by which to identify the most effective exercise to enhance a given group's, subgroup's or individual's CMJ jump height. However, these findings were based on the results (statistical relationships and differences) of an acute study, which required verification with training studies. The combined results of study two and study three (drop jump training intervention studies) did not support the efficacy of the proposed pathway. This was due to the fact that (a) CMJ PRFs were not necessarily true CMJ performance determining factors, and (b) the acute pre-training stress experienced by a given CMJ PRF did not necessarily give an insight into its subsequent post-training change.

Conclusion: Based on findings 'a' and 'b' (above) the use of the proposed pathway to identify the most effective exercise to enhance a given group's, subgroup's or individual's CMJ jump height cannot be supported.

Publications

Publications related to the thesis:

Marshall, B.M and Moran, K.A. 2008. Can biomechanical diagnostic profiling identify the effectiveness of specific training exercises? Proceedings of the 26th Annual Conference on Biomechanics in Sports. Seoul, 14-18 July, 2008.

Other publications:

Moran, K.A., Clark, M., Reilly, F., Wallace, E.S., Brabazon, D., **Marshall, B.M**. 2009. Does endurance fatigue increase the risk of injury when performing drop jumps? *Journal of Strength and Conditioning Research*. 23(5), pp1448-1455.

Moran, K.A., **Marshall, B.M**. 2006. Effect of fatigue on tibial impact accelerations and knee kinematics in drop jumps. *Medicine and Science in Sport and Exercise*. 38(10), pp1836-1842.

Whyte, E.F, Moran, K.A., Shortt, C.P., **Marshall, B.M**. 2010. The influence of reduced hamstring length on patellofemoral joint stress during squatting in healthy male adults. *Gait and Posture*. 31(1), pp 47-51.

Moran, K.A., McGrath, T., **Marshall, B.M**., Wallace, E.S. 2009. Dynamic stretching and golf swing performance. *International Journal of Sports Medicine*. 30(2), pp113-118.

Chapter 1

Introduction

Vertical jumping ability is an important contributor to successful performance in many sports, including volleyball and basketball (Harman et al. 1990; Rodacki et al. 2002). The most common type of vertical jump used in sport is a countermovement jump (CMJ) (Bobbert et al. 1996; Harman et al. 1990). This form of jump utilises a preparatory movement downwards before a vigorous extension of the hip, knee and ankle propels the body upwards (Bobbert et al. 1996). Coaches typically seek to enhance their athletes' CMJ ability (maximal jump height) by prescribing neuromuscular training exercises. Training exercises commonly employed with the aim of enhancing CMJ jump height include the drop jump, squat, jump squat and power clean (Kraemer and Newton 1994; Wilson et al. 1993).

In an attempt to select the most appropriate training exercise to enhance their athletes' jump height a coach may look to the results of previous training studies. However, the outcomes of training studies that have examined the effects of these respective training exercises (e.g. squat, jump squat, drop jump and power clean) on CMJ jump height are generally inconsistent. These inconsistencies typically manifest in three ways. Firstly, there are often conflicting findings regarding whether training with a given exercise can actually improve CMJ jump height or not (Wilson et al. 1996; Weiss et al. 2000). Secondly, even when several studies find an exercise has significantly improved CMJ jump height the magnitude of enhancement can vary quite dramatically across studies (Lyttle et al. 1996; Wilson et al 1993). Thirdly, on several occasions where an exercise has been found to increase a group's mean jump height there is evidence to suggest that a number of individuals within the group did not experience an enhancement (Lyttle et al. 1996) or indeed experienced a decline (Channell and Barfield 2008). It would also appear that there is no compelling evidence to suggest that between study differences in subject characteristics, training intensity, frequency or volume can necessarily explain the inconsistent training outcomes of a given training exercise (Bobbert and Van Soest 1994; Bobbert 1990). The resounding implication of all of this is that coaches cannot be sure as to which training exercise will be most effective at enhancing their athletes' CMJ jump height. Obviously this is not a satisfactory situation, especially when working with elite athletes. There is a need therefore, for researchers to develop pre-training methods of identifying the training exercise that will most effectively enhance an athletes' CMJ jump height. Before developing any pre-training exercise prescription methods it is important to first of all understand why the effects of respective training exercises are often inconsistent.

The theory of training overload states that in order for CMJ jump height to be enhanced the performance determining factors (PDFs) of the CMJ must be challenged by a training stress at a level beyond which they are accustomed (Zatsiorsky and Kraemer 2006). Such training stress, imposed throughout a training period, should lead to an enhancement in the CMJ PDFs (Bobbert et al. 1986a) and in turn jump height. Given the inter-individual variation in response to respective training exercises the question thus becomes why would a given training exercise appropriately stress one individual's CMJ PDFs but not another's? This may be because (a) different individuals may have different CMJ PDFs, and\or (b) different individuals may experience different training stresses while undertaking a given training exercise. Both possibilities are in accordance with the notion that each individual is unique and will possibly possess an individualised neuromusculoskeletal solution (movement strategy) [Bates 1996; Dufek et al. 1995] for both the CMJ and a given training exercise. While there is indirect evidence to support points 'a' (Aragon-Vargas and Gross 1997a) and 'b' (Bobbert et al. 1986a) [above] it appears that no study has directly examined these respective hypotheses.

To this point it has been established that there is a clear need for researchers to develop pre-training methods of identifying the training exercise that will most effectively enhance athletes' jumping ability. Moreover, cognisant of points 'a' and 'b' above, it is apparent that such methods should consider that different individuals (and thus groups) might have different CMJ PDFs and experience different training stresses when utilising a given training exercise. In light of all of this, a biomechanical diagnostic and prescriptive pathway is proposed (Figure 1.1).

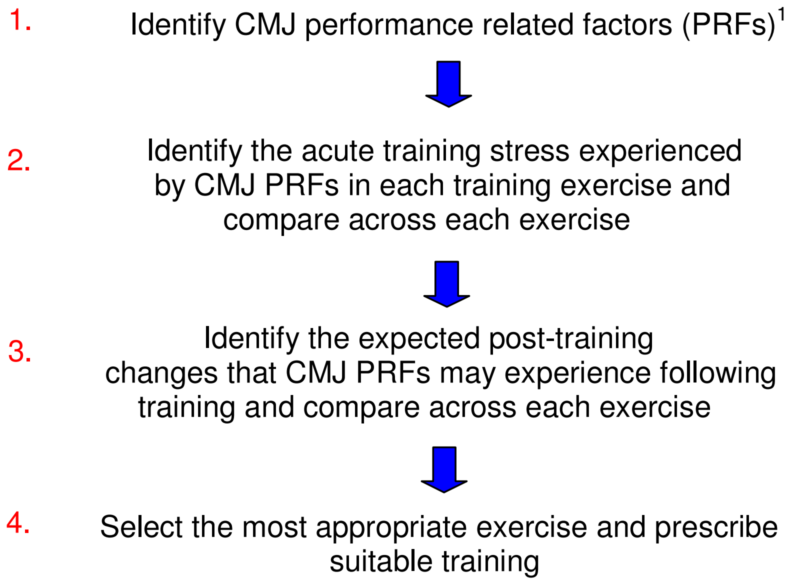

Figure 1.1 A proposed pre-training biomechanical diagnostic and prescriptive pathway

Step one of the proposed biomechanical pathway involves identifying all relevant CMJ performance related factors (PRFs), that is, those CMJ kinetic and kinematic parameters that are significantly correlated with jump height. Step two involves identifying the acute training stress that CMJ PRFs experience in each training exercise. Authors have previously identified acute training stresses by testing for a significant difference between a parameter's magnitude in the CMJ versus its magnitude in a given training exercise (Bobbert et al. 1986a; Holcomb et al. 1996a). The diagnostic phase of the pathway (steps one and two, Figure 1.1) requires a full biomechanical analysis of the CMJ and of each training exercise under examination. It is hoped that the results of such an acute pre-training analysis will provide an insight into the likely enhancements that CMJ PRFs will experience following training with each exercise (step 3). As post-training

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[1] While CMJ PDFs are those CMJ parameters that ultimately determine jump height they cannot be identified experimentally in an acute testing session, as a true cause and effect relationship cannot be established. Instead, CMJ PRFs are identified. CMJ PRFs are those CMJ parameters that are significantly correlated with CMJ jump height. Correlation is necessary for causation and as such CMJ PRFs may be considered potential CMJ PDFs (see section 2.2.2 for more details).

enhancements in CMJ PRFs are assumed to lead to improvements in CMJ jump height, the exercise that is deemed most likely to induce the greatest enhancements in CMJ PRFs would be considered the most appropriate exercise to employ to enhance jump height (step four). Once the most appropriate training exercise is selected all that remains is to prescribe a suitable training regimen and examine its effectiveness.

The statistical techniques employed in step one and two of the pathway (correlation and tests of mean difference, respectively) are typically carried out using group statistical analysis (Bates et al. 2004). In the current application, this form of analysis may allow the identification of the training exercise that is most effective at improving a group's mean jump height. However, it has been suggested that different individuals have different CMJ PDFs (and thus CMJ PRFs) and may experience different training stresses with the same training exercise. Such inter-subject variability may not be appropriately accommodated for in group statistical analyses (Bates et al. 2004; Stergiou and Scott 2005). Thus, in order to identify the most effective training exercise for each individual it may be necessary to identify each individual's CMJ PRFs and acute CMJ PRF training stress. This may be done using a single-subject analysis, which involves statistically analysing repeat performances from one individual (Bates et al. 2004). Unfortunately, some limitations inherent with single-subject analysis may undermine the application of the proposed pathway at an individual subject level; Aragon-Vargas and Gross (1997a) acknowledge that a lack of sufficient intra-subject variability in both CMJ jump height and CMJ parameters is a major concern when attempting to identify CMJ PRFs using single-subject analysis. It may therefore be worth applying the proposed pathway using a combination of both a group and subgroup [cluster] analysis. This may increase the likelihood of prescribing the most effective exercise to the majority of individuals while avoiding the potential limitations of a single-subject analysis.

To summarise, a biomechanical diagnostic and prescriptive pathway has been proposed that could facilitate a pre-training identification of the training exercise that will most effectively enhance a given group's, subgroup's or individual's CMJ jump height. The current study aims to test the efficacy of the proposed pathway with a single acute research study and two training studies. The acute study will examine the hypothesis that different individuals have the potential to have different CMJ PRFs (and thus CMJ PDFs) and experience different training stresses in a given exercise. The acute study will also examine whether the proposed pathway can identify the exercise that will most likely enhance a given group's, subgroup's or individual's CMJ jump height. This is based on the hypothesis that a pre-training stress analysis can provide a pre-training insight into the likely training effect that a given training exercise will have on CMJ jump height. Training studies will subsequently examine this hypothesis using eight weeks of drop jump training. The training studies will also test the following implicit assumptions of the pre-training stress analysis: (a) CMJ PRFs are likely to be true CMJ PDFs, and (b) the acute pre-training stress experienced by a CMJ PRF will give an insight into that CMJ PRFs post-training change.

Chapter 2

Literature review

2. 1 Introduction

As outlined in the previous chapter there is a clear need for researchers to develop pre-training methods of identifying the training exercise that will most effectively enhance an athlete's CMJ jump height. In order to develop such a diagnostic form of exercise prescription it is important to have knowledge of several of the biomechanical factors that may determine CMJ jump height. It is also important to have an understanding of how different training exercises stress (or overload) these potential performance determining factors (PDFs). This review will therefore begin with an introduction to the CMJ and basic jumping mechanics. It will be proposed that a review of potential CMJ PDFs should examine kinetic and kinematic concentric and eccentric parameters at both a whole body and joint level. How researchers typically identify potential CMJ PDFs (using correlation techniques at a group level of analysis) and the inherent limitations of these methodological approaches will be outlined before examining numerous potential CMJ PDFs. A review of several training exercises, namely the drop jump, squat, jump squat and power clean will then follow. The training exercise reviews will be presented independently and each will focus primarily on (a) how the training exercise appears to acutely stress potential CMJ PDFs and (b) the outcomes of training studies that examined the effects of the training exercise on CMJ jump height.

Once each exercise has been reviewed it will become apparent that the outcomes of training studies regarding the effectiveness of a given exercise at enhancing jump height are generally inconsistent. Based on the theory of training overload, and taking into consideration why the results of training studies may be inconsistent in the first place, a biomechanical diagnostic and prescriptive pathway will be proposed. The proposed pathway may facilitate a pre-training identification of the training exercise that will most effectively enhance a given group's, subgroup's or individual's CMJ jump height. The review will end by discussing various methodological issues to be considered when applying the pathway.

2.2 Potential countermovement jump performance determining factors

This section will begin with an introduction to the CMJ and basic jump mechanics (2.2.1). This will be followed by a brief discussion on the means by which researchers typically identify potential CMJ PDFs and inherent limitations with these approaches (2.2.2 and 2.2.3). Sections 2.2.3-2.2.6 will then review several potential concentric phase CMJ PDFs. The role of the countermovement in determining CMJ jump height will be briefly discussed in section 2.2.7, before reviewing several potential eccentric CMJ PDFs (2.2.8 and 2.2.9). Finally, section 2.2.10 will briefly introduce key concepts of CMJ technique and section 2.2.11 will review several potential coordination based CMJ PDFs.

2.2.1 Introduction to the countermovement jump and basic jump mechanics

The countermovement jump begins in an upright standing position where from the jumper lowers their body's centre of mass (COM) through flexion at the hip, knee and ankle joints, before vigorously extending these same joints to propel the body upwards (Figure 2.1) (Bobbert et al. 1996). Typical CMJ jump heights in adult men range from 41cm in physically active subjects to 54cm in proficient volleyball players (Table 2.1). As the COM lowers during the countermovement, the lower extremity extensor muscles primarily act eccentrically (Umberger 1998); whilst as the COM moves upward from its low point until the point of takeoff the lower extremity extensor muscles primarily act concentrically. All muscular actions, including those used during the CMJ, are stimulated by electrochemical messages (action potentials), which are sent from the somatic nervous system to individual muscle fibers via motor neurons (Harris and Dudley 2000). When a motor neuron fires, all the fibers it innervates (the motor unit) are activated and develop force (Harris and Dudley 2000). Motor units are made up of muscle fibers with markedly different physiological characteristics. A common classification scheme delineates between slow twitch and fast twitch motor units (Harris and Dudley 2000). During the CMJ it is the fast twitch (as opposed to slow twitch) motor units that are primarily activated; the former being capable of greater force and power production. Appropriate neuromuscular training may induce certain physiological adaptations, which may facilitate an enhanced ability to produce force and power and thus increase maximal CMJ jump height. These adaptations include: (a) an increased rate of neural firing, (b) an increased synchronisation of neural firing, and (c) muscle fiber hypertrophy.

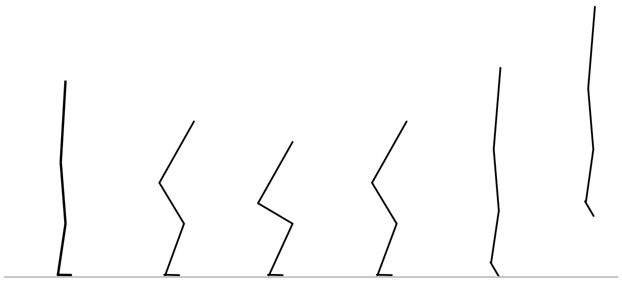

Figure 2.1 A graphical representation of the CMJ

Table 2.1 Typical CMJ jump heights

Author	Subjects	Jump height (cm)
Bobbert et al. (1986a)	13 male Handball	49
Bobbert et al. (1987a)	10 male Volleyball	54
Harman et al. (1990)	18 male Physically active	41
Lees et al. (2004)	20 male Various sports	46
Vanrenterghem et al. (2004)	10 male Soccer	44

In a CMJ, as in any form of jumping, the body can be considered as a projectile, meaning that the height achieved by the COM is ultimately determined by: (a) the vertical velocity of the COM at takeoff, and (b) the vertical position of the COM at takeoff (Aragon-Vargas and Gross 1997b). Improvements in an athlete's maximal jump height however occur mainly through enhancing the vertical velocity of the COM at takeoff rather than enhancing the vertical position of the COM at takeoff (Zajac 1993), the latter being primarily an anthropometrical characteristic. Through the impulse momentum relationship ($F.t = m.\Delta v$) vertical velocity at takeoff is determined by the amount of vertical impulse generated, in excess of that required to support the body's mass, during the concentric phase. The neuromuscular system generates vertical impulse through the active rotation of body segments resulting in a vertical force being exerted against the ground. It follows therefore that neuromuscular output during the concentric phase of the CMJ can be viewed as the key determinant of CMJ jump height. In light of this, various kinetic parameters that can quantify concentric neuromuscular output during the CMJ have been examined as potential CMJ PDFs (Dowling and Vamos 1993). The concentric phase of the CMJ does not however act in isolation; it is preceded by an eccentric phase, with various characteristics of the eccentric phase influencing concentric neuromuscular output and thus jump height (Bobbert et al. 1996; Bosco et al. 1981; Moran and Wallace 2007). It is also widely accepted that jumping technique and coordination, typically quantified using kinematic and temporal parameters (Lees 2000), play an important role in determining CMJ performance (Aragon-Vargas and Gross 1997b; Bobbert and Van Soest 1994; Lees 2000; Vanezis and Lees 2005).

The review of potential CMJ PDFs in this section (2.2) will therefore include both kinetic and kinematic parameters at a whole body and joint level pertaining to both the eccentric and concentric phases.

2.2.2 Performance determining factors versus performance related factors

Within this thesis the author makes a specific delineation between the terms 'performance determining factor' (PDF) and 'performance related factor' (PRF). PDFs are those kinetic and kinematic parameters that ultimately determine CMJ jump height. A CMJ parameter (e.g. peak hip power) may be considered a true PDF when clear experimental evidence of a cause-effect relationship between that parameter and jump height is established. From a purist perspective, to establish a true cause-effect relationship a study would have to involve a training intervention that caused only a single CMJ parameter to be enhanced and subsequently establish a direct relationship between this enhancement and an increase in jump height. However, it is clearly impossible to isolate and enhance a single CMJ kinetic or kinematic variable. The author believes that the strongest evidence that a given CMJ parameter is a PDF is when, following a training intervention, the magnitude of increase in the given parameter is directly related to the magnitude of increase in jump height.

In contrast, a CMJ PRF is referred to where a given parameter's magnitude is directly related to the magnitude of jump height, that is, the relationship is based on data from an acute testing session with no training intervention. Clearly, a PRF does not directly show a cause-effect relationship.

The vast majority of previous studies invariably refer to CMJ PRFs as they only examine this type of relationship (Dowling and Vamos 1993; Harman et al. 1990; Jaric et al. 1989). As far as this author is aware only one study, Sheppard et al. (2009), identified what could be considered a true CMJ PDF by finding a significant ($p<0.05$) correlation between the post-training change in peak force and jump height ($r = 0.55$).

2.2.3 Group analysis versus single subject analysis

Statistical techniques employed in biomechanical research, including bi-variate correlation and tests of mean difference, are typically carried out using group statistical analysis (Bates et al. 2004). Not surprisingly therefore, the majority of studies that have identified CMJ PRFs (for example Dowling and Vamos 1993, Harman et al. 1990 and Jaric et al. 1990), have done so by gathering representative data from individuals in order to identify a specific group's CMJ PRFs. There is reason to suggest however, that a group's CMJ PRFs may not necessarily be representative of every individual's CMJ PRFs.

Bates et al. (1996) suggest that each individual is unique and thus different individuals have the potential to have a unique neuromuscular solution (movement strategy) for a given task. This uniqueness is likely due to inter-individual differences in neuromuscular capacity (e.g. joint power, joint dominance), anthropometrics (e.g. limb lengths), muscle morphology (e.g. percentage muscle fiber type), preferred technique and past-training experience. In light of the theory that different individuals may possess a unique neuromuscular solution for a given task (Bates et al. 1996) it could be suggested that different individuals may have different CMJ PDFs (and thus CMJ PRFs). A group analysis is not sensitive to such inter-subject variability (Bates et al. 1996) and thus individual level CMJ PRFs may be hidden. Bates et al. (1996) therefore suggest using a single-subject analysis in order to avoid losing pertinent information at the individual subject level. A single subject analysis involves statistically analysing repeat performances from one individual.

As far as this author is aware only one study, Aragon-Vargas and Gross (1997a), has directly identified individual level CMJ PRFs using a single-subject analysis. Using multiple regression techniques these authors provide evidence of the potential for inter-individual differences in CMJ PRFs (and thus CMJ PDFs). For example, the amplitude of the body's COM was the best single predictor of CMJ jump height (r = 0.56) for individual A (pp54) but, contrastingly, was not a notable predictor of jump height for individual B (pp55). This study also highlights the inherent limitations of using a group analysis in the presence of such inter-individual differences. For example, no ankle kinetic parameters appeared in the predictor models of jump height at the group level but several ankle parameters were present in models at an individual level (Aragon-Vargas and Gross 1997a and b). That is, these individual level CMJ PRFs appear to have been hidden in the group analysis.

The remainder of this section (2.2) will review several potential CMJ PDFs (as well as provide some background information on the influence of the countermovement and CMJ coordination on CMJ jump height).

2.2.4 Concentric whole body kinetic parameters as potential CMJ PDFs

A vertical ground reaction force–time curve of a CMJ is presented in Figure 2.2. The point of transition from eccentric to concentric phase, which may be obtained from COM positional data (i.e. the low point of the COM), is identified. The vertical impulse generated in excess of that required to support the body's mass (jump impulse) can be graphically represented as the area under the concentric portion of the vertical ground reaction force trace (Figure 2.2). Better jumpers will produce more vertical jump impulse than poorer ones but such knowledge provides little insight into potential determining factors of jump impulse or indeed jump performance. Instead, researchers typically examine discrete aspects of the vertical ground reaction force trace, such as peak concentric force and concentric rate of force development, as potential CMJ PDFs.

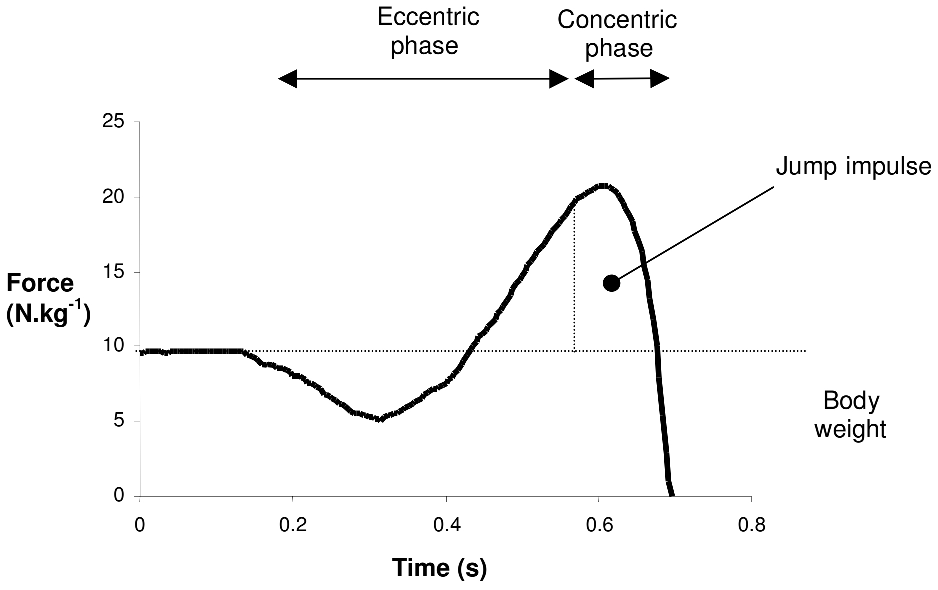

Figure 2.2 Vertical ground reaction force-time curve of a CMJ

Harman et al. (1990) and Dowling and Vamos (1993) both found significant correlations between peak force and CMJ jump height of r = 0.53 and 0.52, respectively. Moreover, Shepard et al. (2009) found that increases in peak force over a twelve month training period were significantly correlated (r = 0.55) with increases in CMJ jump height in elite male volleyball players. This latter study appears to be the only study to have identified true CMJ PDFs, while other studies more typically identify CMJ PRFs (see section 2.2.2 for more details). It is worth noting that Dowling and Vamos (1993) observed some jumps with large force that were not necessarily high jumps. This led these authors to contend that while high peak forces may be required for good performance they are not necessarily indicative of higher jumps. Typical CMJ peak concentric force values are presented in Table 2.2.

Table 2.2 CMJ whole body peak force (concentric phase)

Author	Subjects	Peak force ($N.kg^{-1}$)
Bobbert et al. (1987a)	10 male Volleyball	24.7
Cormack et al. (2008)	15 male Australian football	23.0
Cormie et al. (2009)	14 male Inactive	21.0
Harman et al. (1990)	18 male Physically active	22.7
Hori et al. (2009)	24 male Physically active	23.2

Schmidtbleicher (1992) suggests that in dynamic tasks where external loads are low and the time to apply maximal forces are restricted, the rate of force development (RFD) becomes of more decisive importance. It could be argued that the CMJ meets these criteria as no additional external loads other than body weight are moved and a relatively short concentric phase time (typically 280ms to 330ms, Table 2.9) exists. However, force is also developed during the eccentric phase of the CMJ which means that force levels at the onset of the concentric phase are already relatively high (Bobbert et al. 1996). The presence of a countermovement in the CMJ would appear to reduce the importance of concentric RFD in the CMJ as opposed to its importance in concentric only tasks such as the squat jump (Bobbert and Van Zandwijk 1999). While Dowling and Vamos (1993) found no correlation between RFD and CMJ jump height, r = 0.03, their RFD calculation spanned both eccentric and concentric phases (slope between minimum and maximum force). Cormie et al. (2009) and Moir et al.

(2009) report concentric only RFD values of 25.3N.s^{-1} and 23.2N.s^{-1} respectively but as far as this author is aware the relationship between concentric RFD and CMJ jump height has not previously been investigated.

As CMJs require large propulsive forces coupled with high velocities of movement several researchers have investigated measures of whole body power output (power = force x velocity) as potential CMJ PDFs. A typical power-time curve produced during a CMJ is presented in Figure 2.3. Dowling and Vamos (1993), Aragon-Vargas and Gross (1997a) and Harman et al. (1990) all found significant and strong correlations between peak power and jump height (r = 0.93, 0.72 and 0.86, respectively). Moreover, in what appears to be the only previous study to employ a single-subject analysis to identify an individual subject's CMJ PRFs, Aragon-Vargas and Gross (1997b) found that peak power was included in best predictor models (multiple regression was employed) of the CMJ for the three subjects whose results were presented in detail. Typical CMJ peak concentric power values are presented in Table 2.3.

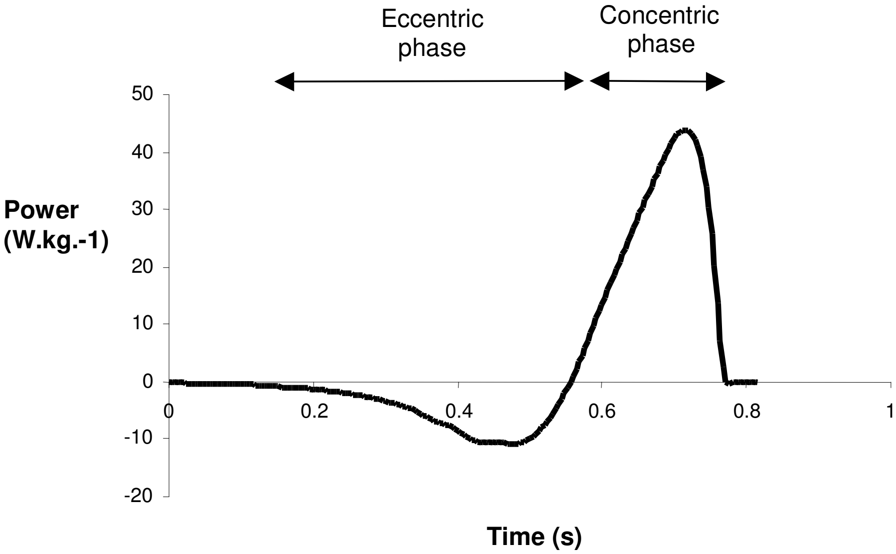

Figure 2.3 Power-time curve of a CMJ

Table 2.3 CMJ whole body peak power (concentric phase)

Author	Subjects	Peak power ($W.kg^{-1}$)
Aragon-Vargas and Gross (1997a)	52 male Physically active	52.0
Cormack et al. (2008)	15 male Australian football	53.9
Cormie et al. (2009)	14 male Inactive	55.9
Harman et al. (1990)	18 male Physically active	43.1
Hori et al. (2009)	24 male Physically active	54.2

In the same vein as rate of force development, rate of power development may also be an important contributor to CMJ jump ability. However, it appears that no previous studies have examined the relationship between whole body rate of power development and CMJ jump height.

While Cormie et al. (2009) found that skilled jumpers produced significantly ($p<0.05$) more concentric work than non-skilled jumpers in a CMJ, it would appear that no authors have examined the direct relationship between whole body concentric work done and CMJ jump height. Typical values of concentric work done in the CMJ are presented in Table 2.4.

Table 2.4 CMJ whole body work done (concentric phase)

Author	Subjects	Work done ($J.kg^{-1}$)
Bobbert et al. (1986a)	13 male Handball	7.9
Hubley and Wells (1983)	6 male Physically active	8.5
Vanrenterghem et al. (2004)	10 male Volleyball	7.6

2.2.5 Concentric joint kinetic parameters as potential CMJ PDFs

The concentric force produced at a whole body level during the CMJ is the sum of the concentric moments produced at each joint. Thus, while various whole body kinetic parameters may be considered CMJ PDFs they are in turn determined by joint-level kinetics. A greater insight into the PDFs of CMJ jump height can thus be achieved by identifying potential joint level CMJ PDFs (Aragon-Vargas and Gross 1997b; Vanezis and Lees 2005).

Several researchers have quantified peak concentric hip, knee and ankle moments produced during the CMJ (Table 2.5). While Vanezis and Lees (2005) found that each joint produced comparable peak moments, Aragon-Vargas and Gross (1997b) found a much larger moment at the hip in comparison to the knee and ankle. Other inter-group differences are also apparent. Bobbert et al. (1987a) found a larger peak moment at the knee compared with the ankle, while Vanrenterghem (2008) found the opposite (Table 2.5). These inter-group differences appear to arise from inter-individual differences in jumping strategies (Vanezis and Lees 2005). Vanezis and Lees (2005) found that several individuals in their study emphasised the knee during the CMJ, while others emphasised the hip. In light of these observations, it could be theorised that while peak moment at a given joint could be a determining factor of CMJ jump height for one individual, peak moment at a different joint may be a determining factor for another. Indeed, evidence of a potential for inter-individual differences in the joint moments considered to be CMJ PRFs exists in the literature. Aragon-Vargas and Gross (1997b) found that peak concentric hip moment was considered one of the best single predictors of jump height (r = 0.53) in their group analysis. However, in their single-subject analysis the same authors found that ankle concentric peak moment, rather than hip peak moment, was included in the best CMJ jump height predictor model for subject A, while peak ankle moment was not included in predictor models of CMJ jump height for subjects B or W (Aragon-Vargas and Gross 1997a). This is clear evidence that different individuals may have different CMJ PRFs, which would suggest that different individuals may have different CMJ PDFs. The findings of Aragon-Vargas and Gross (1997a,b) also highlights that group level CMJ PRFs, as identified using a group analysis, are not necessarily an accurate reflection of every individual's CMJ PRFs (as suggested in section 2.2.3).

Table 2.5 CMJ peak joint moments (concentric phase)

Author	Subjects	Peak moment ($Nm.kg^{-1}$)	
Aragon-Vargas and Gross (1997a)	52 male Physically active	Hip Knee Ankle	4.0 3.0 3.3
Bobbert et al. (1986a)	13 male Handball	Hip Knee Ankle	4.7 3.7 3.4
Bobbert et al. (1987a)	10 male Volleyball	Hip Knee Ankle	5.0 4.3 3.1
Vanezis and Lees (2005)	9 male Soccer (high group)	Hip Knee Ankle	3.5 3.4 3.1
	9 male Soccer (low group)	Hip Knee Ankle	3.1 3.1 2.8
Vanrenterghem et al. (2008)	20 male Various sports	Hip Knee Ankle	~3.7* ~2.8* ~3.2*

* Value estimated from graph

No studies appear to have investigated a direct relationship between joint level concentric rate of moment development and CMJ jump height, but Vanezis and Lees (2005) provide indirect evidence of its importance. These authors noted that better jumpers had a larger rate of moment development at each joint than poorer jumpers (based solely on graphical observations, relationships were not tested statistically).

Several authors have quantified CMJ joint concentric peak power magnitudes (Table 2.6) and it would appear that knee and ankle peak power values are consistently higher than those at the hip. In spite of this, peak hip power has been found to be a CMJ PRF in previous studies. Vanrenterghem et al. (2008) found that hip concentric peak power was significantly correlated with CMJ jump height ($r = 0.68$), and in their group analysis Aragon-Vargos and Gross (1997b) found that hip peak power was consistently included in the best predictor models of CMJ jump height and was the best single predictor of CMJ jump height at the joint level ($r = 0.66$). The single-subject analysis carried out by Aragon-Vargas and Gross (1997a) also found that hip concentric peak power was considered a significant jump height predictor for most of the individuals examined.

Table 2.6 CMJ peak joint powers (concentric phase)

Author	Subjects	Peak power ($W.kg^{-1}$)	
Aragon-Vargas and Gross (1997a)	52 male Physically active	Hip Knee Ankle	16.3 20.1 25.9
Bobbert et al. (1986a)	13 male Handball	Hip Knee Ankle	19.5 20.6 24.4
Bobbert et al. (1987a)	10 male Volleyball	Hip Knee Ankle	18.0 30.1 28.9
Vanezis and Lees (2005)	9 male Soccer (high group)	Hip Knee Ankle	15.9 18.5 21.6
	9 male Soccer (low group)	Hip Knee Ankle	12.6 15.6 17.1
Vanrenterghem et al. (2008)	20 male Various sports	Hip Knee Ankle	~15.9* ~15.3* ~19.4*

* Value estimated from graph

Findings regarding the importance of peak knee and ankle powers to CMJ jump height are more equivocal. For example, while Vanezis and Lees (2005) found that the only significant difference between ‘good’ and ‘poor’ jumpers in terms of joint power magnitudes was ankle concentric peak power, Vanrenterghem et al. (2008) found that ankle concentric peak power was not significantly correlated with CMJ jump height (r = 0.18). In addition, while Aragon-Vargas and Gross (1997b) found that knee concentric peak power was included in several best predictor models of CMJ jump height at the group level, Vanrenterghem et al (2008) found that this parameter was not correlated with jump height (r = -0.12) for their particular group.

No studies appear to have investigated a direct relationship between joint level concentric rate of power development and CMJ jump height but Vanezis and Lees (2005) provide indirect evidence of its importance. These authors noted that better jumpers had a larger rate of power development at each joint than poorer jumpers (based solely on graphical observations, relationships were not tested statistically).

Numerous studies have quantified the amount of total concentric work done at the hip, knee and ankle in the CMJ (Table 2.7). The relative contribution of each joint to total work done is often also calculated as a means of identifying which muscle group is dominant during the CMJ (Table 2.7). While the majority of studies found that the hip joint produces the greatest amount of concentric work done followed by the knee then the ankle (Table 2.7), Hubley and Wells (1983) found that the greatest amount of work was done at the knee followed by the hip then the ankle. These inconsistencies may be explained by the fact that there is much inter-subject variability in how individuals produce concentric work done (Bobbert et al. 1986a; Hubley and Wells 1983; Jaric et al. 1989). Some studies have provided indirect evidence that concentric work done at a given joint may be considered a potential CMJ PDF. For example, Lees et al. (2004) found that as jumps progressed from sub-maximal to maximal the amount of work done at the hip increased significantly, while work done at the knee and ankle experienced no notable change. In addition Vanezis and Lees (2005), in their comparison of ‘good’ versus ‘poor’ performers of the CMJ, found that concentric work done at the ankle (not the hip or knee) was significantly greater in the ‘good’ group in comparison to the ‘poor’ group.

Table 2.7 CMJ joint work done and percentage joint contribution to total whole body work done (concentric phase)

Author	Subjects	Work done (J.kg^{-1})		Percentage contribution	
Bobbert et al. (1986a)	13 male Handball	Hip	2.8	Hip	38
		Knee	2.3	Knee	32
		Ankle	2.2	Ankle	20
Fukashiro and Komi (1987)	1 male	Hip	2.3	Hip	51
		Knee	1.5	Knee	33
		Ankle	0.7	Ankle	16
Hubley and Wells (1983)	6 male Physically active	Hip	2.4	Hip	28
		Knee	4.1	Knee	49
		Ankle	2.0	Ankle	23
Lees et al. (2004)	20 male Various sports	Hip	3.2	Hip	44
		Knee	2.1	Knee	29
		Ankle	1.9	Ankle	27
Vanezis and Lees (2005)	9 male Soccer (high group)	Hip	3.2	Hip	43
		Knee	2.3	Knee	29
		Ankle	2.2	Ankle	28
	9 male Soccer (low group)	Hip	2.5	Hip	41
		Knee	2.1	Knee	31
		Ankle	1.8	Ankle	28

2.2.6 Concentric whole body and joint kinematic parameters as potential CMJ PDFs

The amplitude of the COM, as defined in this thesis, is the vertical difference between the body's COM position when standing and the body's COM position when at its lowest point at the end of the countermovement. Larger COM amplitudes during the CMJ provide a greater potential for concentric impulse generation and in turn greater jump heights. Aragon-Vargas and Gross (1997b) found that the amplitude of the COM was included in almost all of the best predictor models of jump height. Similar results were found for many of the individual subjects in their individual subject level analysis (Aragon-Vargas and Gross 1997a). Greater amplitudes of movement however require a greater depth of countermovement and too large a countermovement may place the body in a sub-optimal body orientation to produce maximal force at the start of the concentric phase. In light of this some individuals may benefit from increased COM amplitudes while others, who already utilise optimal COM amplitudes, may not. Typical CMJ COM amplitudes are detailed in Table 2.8.

Table 2.8 Amplitude of the COM from its position at the onset of the concentric phase relative to its position in flat foot standing

Author	Subjects	Amplitude (cm)
Bobbert et al. (1986a)	13 male Handball	35.0
Harman et al. (1990)	18 male Physically active	35.0
Hunter and Marshall (2002)	50 male Physically active	37.6
Moir et al. (2009)	35 male Physically active	40.0
Vanrenterghem et al. (2004)	10 male Volleyball	32.0

The amplitude of concentric COM movement in the CMJ is primarily determined by the maximum angular displacement of the hip, knee and ankle joints following the countermovement. Numerous studies have quantified the peak flexion angle achieved by joints during the CMJ, which is commonly referred to as the angle at joint reversal (reversal from eccentric to concentric phases) [Table 2.10]. It would appear however that no studies have examined the direct relationship between angles at joint reversal (at the hip, knee and ankle) and CMJ jump height. It seems logical to suggest that an optimum range of joint flexion exists for effective CMJ jump heights and while some individuals may benefit from increases\decreases in certain joint angles at reversal, others may not.

Table 2.9 CMJ joint angles at joint reversal

Author	Subjects	Joint angle (degrees)	
Bobbert et al. (1986a)	13 male Handball	Hip Knee Ankle	69.3 76.8 76.8
Bobbert et al. (1987a)	10 male Volleyball	Hip Knee Ankle	70.5 80.2 70.5
Bobbert et al. (1996)	6 male Volleyball	Hip Knee Ankle	64.2 75.1 72.2
Rodacki et al. (2002)	12 male Various sports	Hip Knee Ankle	68.6 89.5 94.1
Van Soest et al. (1985)	10 male Volleyball	Hip Knee Ankle	71.0 79.1 69.3

Concentric phase durations in the CMJ have been found to range from 280ms to 330ms (Table 2.9). Larger concentric phase durations will allow more time for concentric impulse generation and therefore potentially allow greater vertical velocities at takeoff. However, a longer duration concentric phase over the same concentric amplitude would be associated with a reduced COM velocity and in turn lower jump heights. Clearly, as was the case for COM amplitude, increases in concentric phase duration may lead to jump height enhancements for some individuals but have no effect or indeed reduce performance for others. This may in part explain why Aragon-Vargas and Gross (1997a,b) found that concentric phase duration was not related to CMJ jump height in their group level analysis but was related to jump height for a number of individuals in their individual level analysis.

Table 2.10 CMJ concentric phase duration

Author	Subjects	Duration (ms)
Aragon-Vargas and Gross (1997a)	52 male Physically active	316
Bobbert et al. (1986a)	13 male Handball	280
Bobbert et al. (1987a)	10 male Volleyball	290
Bobbert et al. (1996)	6 male Volleyball	330
Rodacki et al. (2002)	11 male Physically active	319
Van Soest et al. (1985)	10 male Volleyball	284

During the last 30ms before takeoff in the CMJ, force production capacity is reduced as the hip and knee extensors have already contracted maximally leaving only the smaller plantar flexors to contribute to force production (Harman et al. 1990). As a result of this the COM is actually decelerating in the final portion of the CMJ concentric phase (Harman et al. 1990). Clearly, in order to maximise jump height, one wishes to minimise any COM deceleration during the concentric phase. Authors have thus suggested that an ability to minimise the time period between peak neuromuscular output and takeoff may well be a CMJ PDF (Harman et al. 1990; Dowling and Vamos 1993). Indeed both Harman et al. (1990) and Dowling and Vamos (1993) found significant negative correlations between jump height and the time between peak power and takeoff (r = -0.78 and r = -0.41, respectively).

2.2.7 Enhancement of jump height due to countermovement

It has been shown that a muscle can produce more concentric work done when it is preceded by an active pre-stretch than when it is preceded by either rest or an isometric contraction (Asmussen and Bonde-Petersen 1974; Moran and Wallace 2007). Such an eccentric-concentric coupling of muscular activity is commonly referred to as a stretch-shortening cycle (SSC). Variations of the vertical jump, often the CMJ and the squat jump, have been employed by researchers to investigate the SSC in complex movements. The squat jump, which is initiated from a semi-squat position without a preparatory countermovement, does not employ a SSC while the CMJ does. There is much evidence to suggest that maximal jump height in a CMJ is greater than that in the squat jump with percentage differences ranging from 5.2% to 18.1% (Table 2.11). A greater jump height in the CMJ compared to the squat jump appears to be due to an enhanced concentric mechanical output in the former. For example, Bosco et al. (1981) found that in jumps of similar knee amplitude, average positive force was 66% greater in a CMJ than in a squat jump.

Table 2.11 A comparison of typical squat jump and CMJ jump heights

Author	Subjects	CMJ (cm)	Squat jump (cm)	Percentage difference
Asmussen and Bonde-Petersen (1974)	14 male 5 female	38.6	36.6	5.2*
Bobbert et al. (1996)	6 male Volleyball	48.1	44.7	7.1*
Bosco and Komi (1979)	34 male Physically active	41.6	35.9	13.7*
Harman et al. (1990)	18 male Physically active	29.1	27.4	5.8*
Moran and Wallace (2007)	17 male Volleyball	31.0	25.4	18.1*

* Significant difference ($p<0.05$)

Several possible mechanisms have been proposed that may explain why CMJ performance is greater than squat jump performance:

(a) High levels of force are developed in the eccentric phase of the CMJ so that at the onset of the concentric phase the extensor muscles are already exerting relatively high forces (Bobbert et al. 1996). This is in contrast to the squat jump where forces at the start of the concentric phase are much lower (Bobbert et al. 1996). As it takes time for muscles to develop force and reach maximal output levels a portion of the work produced in the concentric phase of the squat jump is sub-maximal (Bobbert et al. 1996).

(b) During the eccentric phase of the CMJ potential energy is stored in stretched series elastic elements, primarily in tendons and titin, which may be re-utilised in the subsequent concentric phase (Bobbert et al. 1996).

(c) The stretching of muscles under tension, as is the case in the eccentric phase of the CMJ, may result in muscle spindles initiating a spinal reflex action (Bobbert et al. 1996). This reflex action would increase muscle extensor stimulation and thus output during the subsequent concentric phase.

(d) The eccentric phase of the CMJ may alter the properties of the contractile machinery resulting in enhanced concentric output (Cavagna et al. 1968). This mechanism, referred to as "potentiation", does not appear to be fully explained however.

While there is no overwhelming evidence supporting any one mechanism of SSC enhancement, researchers have identified several common aspects of eccentric-concentric coupling dynamics that are important determinants of effective SSC utilisation. The magnitude of the stretch (Cavagna et al. 1968), the magnitude of the stretch load (Bobbert et al. 1986b), the speed of the stretch (Bosco et al. 1981), the force at the end of the stretch (Bobbert et al. 1996) have all been reported to be of significance. Increases in the magnitude of these eccentric parameters, up to a certain magnitude, may be expected to enhance concentric force output and thus jump height.

Given that the eccentric phase of the CMJ has a large influence on concentric phase mechanical output, and in turn CMJ jump height, various eccentric kinetic and kinematic parameters should be considered as potential CMJ PDFs.

2.2.8 Eccentric whole body and joint kinetic parameters as potential CMJ PDFs

Consistent CMJ eccentric impulse values ranging from 1.2-1.4$N.s^{-1}.kg^{-1}$ have been reported in the literature (Aragon-Vargas and Gross 1997a; Harman et al. 1990; Moir et al. 2009) and while Bosco and Komi (1979) found a significant correlation between eccentric impulse and CMJ jump height ($r = 0.62$), Dowling and Vamos (1993) found a 'poor correlation' (r value not provided). A possible reason for such inconsistent findings is that while a certain amount of eccentric impulse is required for optimisation of SSC mechanics, larger amounts are not associated with further increases in jump height (Dowling and Vamos 1993). This may also explain why in their single-subject analysis, Aragon-Vargas and Gross (1997a) found that eccentric impulse displayed a positive relationship within the best predictor models for subjects A and W, but a negative relationship for subject B. Such inter-individual differences are not accommodated for in group statistical analyses (Bates et al 2004; Stergiou and Scott 2005) with a result that the CMJ PRFs identified for the group may not be an accurate reflection of each individual's PRFs. This appears to have occurred in the studies of Aragon-Vargas and Gross (1997a and b) as eccentric impulse was not included in any of the best predictor models of CMJ jump height at a group level, but was for a number of individuals.

Dowling and Vamos (1993) suggest that a ratio of negative to positive impulse may provide a more sensitive variable to the loading dynamics required for effective SSC utilisation. Indeed, these authors found a ratio of negative to positive impulse to be significantly correlated with CMJ jump height ($r = -0.51$). As far as this author is aware no other authors have investigated a direct relationship between CMJ jump height and a ratio of eccentric to concentric loading.

Peak eccentric force output occurs at the end of the eccentric phase as large forces are required to reverse the downward acceleration of the COM. Whole body force values at the end of the eccentric phase typically range between 19.0 – 22.4N.kg^{-1} (Bobbert et al. 1986a; Cormie et al. 2009). Larger forces at the end of the eccentric phase may allow the neuromuscular system to exploit the most favourable part of the force-velocity curve (Lees 2000), and stimulate a greater SSC utilisation, thus allowing greater subsequent concentric work production. Surprisingly, however, few authors have investigated whole body force at the end of the eccentric phase (or joint moments at joint reversal) as potential CMJ PDFs. Aragon-Vargas and Gross (1997a and b) found that hip moment at joint reversal was one of the best single predictors of CMJ jump height at the joint level ($r = 0.48$) and was included in several of the best predictor models of CMJ jump height, both for the group and for several individual subjects. Typical joint moments at joint reversal are outlined in Table 2.12 and while larger moments were found at the hip followed by the knee and then the ankle in the majority of the studies presented, Voigt et al (1995) found the largest moment at the knee.

Table 2.12 CMJ joint moments at joint reversal

Author	Subjects	Moment ($Nm.kg^{-1}$)	
Bobbert et al. (1986a)	13 male Handball	Hip Knee Ankle	4.0 3.1 2.8
Bobbert et al. (1996)	6 male Volleyball	Hip Knee Ankle	4.1 3.6 2.8
Bobbert et al. (1987a)	10 male Volleyball	Hip Knee Ankle	4.8 3.7 3.1
Voigt et al. (1995)	6 male Skilled jumpers	Hip Knee Ankle	4.1 6.5 2.2

Other measures of eccentric loading that may be related to SSC function (and therefore CMJ jump height) include whole body and joint level powers and work done. It appears, however, that very few authors have tested such relationships statistically, with an exception being Dowling and Vamos (1993) who found a significant but small correlation (r = 0.30) between eccentric peak power and CMJ jump height.

2.2.9 Eccentric whole body and joint kinematic parameters as potential CMJ PDFs

The speed of the stretch phase in a dynamic SSC movement is considered to be one of the limiting factors of SSC utilisation; all else remaining equal, quicker stretches are associated with larger concentric phase enhancements (Bosco et al. 1981). In light of this, both eccentric phase duration and peak negative vertical velocity may be potential CMJ PDFs. It would appear however, that few studies have directly investigated such relationships; an exception being Dowling and Vamos (1993) who found a significant, but small, correlation between peak negative vertical velocity and CMJ jump height (r = 0.30). Typical CMJ eccentric phase durations are outlined in Table 2.13.

Table 2.13 CMJ eccentric phase duration

Author	Subjects	Duration (ms)
Bobbert et al. (1987a)	10 male Volleyball	550
Jaric et al. (1990)	39 male Physically active	530
Knudson et al. (2001)	10male,10 female Physically active	547
Ugrinowitsch et al. (2007)	10 male Physically active	496
Vanrenterghem et al. (2004)	10 male Volleyball	640

In jumps of the same COM amplitude, a stiffer lower extremity would be associated with greater eccentric force development (Hunter and Marshall 2002). Given that variations in eccentric loading influence concentric neuromuscular output and jump height (Moran and Wallace 2007), eccentric whole body and joint stiffness may be considered potential CMJ PDFs. While Hunter and Marshall (2000) found that both CMJ jump height and CMJ eccentric whole body stiffness increased following a period of drop jump training, they did not examine if the change in stiffness was related to the increase in jump height.

2.2.10 Countermovement jump coordination

Neuromuscular output in the CMJ is not only determined by neuromuscular capacity but also by the coordination pattern employed to effectively utilise the capacity of muscles (Bobbert and Van Soest 2001). CMJ coordination can be described as an aspect of jumping technique pertaining to the sequencing and timing of segmental actions (Hudson 1986). Numerous authors contend that CMJ coordination plays an important role in determining CMJ jump height (Bobbert and Van Soest 1994; Hudson 1986; Lees 2000; Rodacki et al. 2001; Tomioka et al. 2001) and several vertical jump simulation studies have demonstrated its importance. For example, Bobbert and Van Soest (1994) found that increasing the force production capacity (strength) of the lower extremity musculature by 20% induced an enhancement in jump height of 7.8cm, but the enhancement only occurred after jump coordination was re-optimised. In fact, jump height declined by 2.0cm when the musculature was strengthened and the coordination strategy for the original muscular capacity was maintained.

CMJ coordination strategies are organised by the central nervous system in light of various constraints imposed on the system. These constraints reduce the number of degrees of freedom available to the system when producing the CMJ (Van Ingen Schenau 1989). Before discussing the potential for various coordination parameters to be CMJ PDFs (section 2.2.11) it is important to have an understanding of some of these constraints (a-e below).

(a) Task constraint

CMJ jump height is determined by the effective energy of the COM at takeoff, which in turn is determined by the sum of the COM's kinetic energy (vertical velocity) and the COM's potential energy (vertical position) (Bobbert and Van Ingen Schenau 1988). The task constraint of the CMJ is therefore to maximise the effective energy of the COM at takeoff by optimally enhancing both its vertical velocity and vertical position at takeoff. Bobbert and Van Soest (2001) contend that a proximodistal sequence of segmental action (hip followed by knee followed by ankle) allows the uni-articular extensors of the lower extremity to produce as much work and be as fully extended as possible at takeoff. Thus this sequence of segmental action would appear to be the most optimal to deal with the task constraint of the CMJ.

(b) Geometrical constraint

Vertical velocity of the COM is increased through the rotations of lower body segments, but as a segment becomes more extended (more vertical) the transfer of angular velocity to vertical velocity diminishes (Bobbert and Van Soest 2001). The fact that the lower extremity musculoskeletal system consists of both uni- and bi-articular muscles (see Figure 2.4) may, in part, compensate for the geometrical constraint (Van Ingen Schenau 1989). For example, mechanical energy created by the gluteus maximus in extending the hip contributes less and less to effective energy at takeoff the more extended the hip becomes (Van Ingen Schenau 1989).

However, through the bi-articular rectus femoris some of this energy is transported to the knee joint to assist in knee joint extension (Van Ingen Schenau 1989). Similarly, mechanical energy can be transported from the knee joint to the ankle joint via the gastrocnemius (Bobbert et al. 1986b).

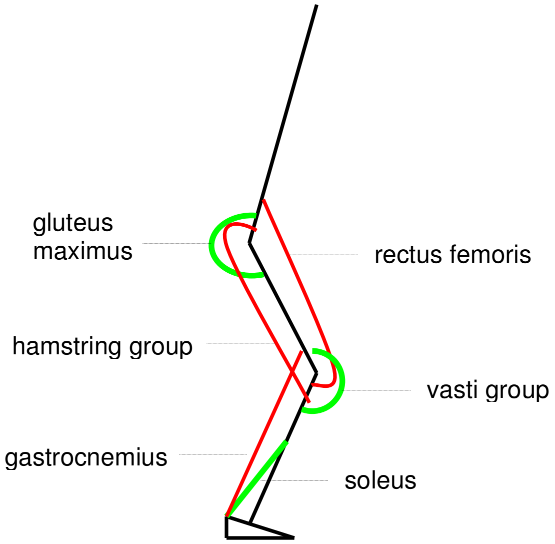

Figure 2.4 The major uni- and bi-articular muscles utilised in the CMJ

(c) Anatomical constraint

As joints reach maximal extension in the latter portion of the concentric phase it is necessary to decelerate their high angular velocities to prevent a damaging hyper extension of joints (Van Ingen Schenau 1989). If this deceleration was carried out by uni-articular muscles alone this would limit the range over which they could contribute to the body's effective energy and significant rotational energy would be lost as heat (Van Ingen Schenau 1989). However, through the use of bi-articular muscles the system can actually decelerate a proximal joint and distribute the energy required to do so to assist in joint extension at a distal joint (Van Ingen Schenau 1989).

(d) Intersegmental constraint

A muscular action at one joint can act to accelerate another joint it does not span due to inertial forces being transmitted from one segment to another (inertial coupling) (Zajac 1993). For example, at the initiation of the concentric phase of the countermovement jump a powerful extension of the hip joint will create an inertial force that will attempt to flex the knees and dorsiflex the ankles (Bobbert and Van Zandwijk 1999; Bobbert and Van Ingen Schenau 1988b). Thus, knee and ankle moments must be increased at the initiation of the CMJ to provide a stable base about which the hip can move affectively (Bobbert and Van Zandwijk 1999).

(e) Moment distribution constraint

To most effectively project the body vertically during a CMJ the vertical velocity of the COM at toe-off must be directed as vertically as possible; a deviation forward or backward will lead to unwanted forward or backward rotation of the COM during flight and reduce jump height. Bobbert and Van Zandwijk (1999) propose that knee and ankle moments create an upward backward movement of the COM while a hip moment causes an upward forward movement. They suggest that a proximodistal sequence of segmental action results in an initial upward forward movement of the COM followed by an upward backward movement, resulting in an almost perfectly vertical velocity of the COM at takeoff (Bobbert and Van Zandwijk 1999).

2.2.11 Coordination parameters as potential CMJ PDFs

Aragon-Vargas and Gross (1997b) found that a proximodistal sequence of joint reversals was not included in several best predictor models of CMJ jump height. Somewhat similarly Ravn et al. (1999) found that in a subgroup of volleyball players (skilled jumpers) seven individuals displayed a proximodistal sequencing of joint reversals and peak moments, while six displayed a simultaneous pattern. In addition, while it would appear that a hip before knee and ankle sequence of segmental action is quite common among individuals, the sequencing of knee and ankle actions are much more variable (Aragon-Vargas and Gross 1997b; Rodacki et al. 2001). The findings of these studies suggest that a fully proximodistal sequence of joint action is not as common nor as important a determinant of CMJ jump height as would be expected based on the apparent functionality of such a sequencing (see section 2.2.10). In fact Hudson (1986) suggests that it is the timing of segmental actions (i.e. the net time difference between actions at adjacent segments) that are more important to maximal CMJ jump height achievement than their sequencing (i.e. whether or not the given action occurs at the proximal segment before the distal segment). When comparing good versus poor jumpers the authors found that better jumpers had shorter time delays between adjacent segments at the start of, and end of, the concentric phase (Hudson 1986). In addition, Hudson (1986) suggests that synchronisation between the hip and knee joint seems to be more important than synchronisation between the knee and ankle. Aragon-Vargas and Gross (1997a) suggest that the ideal timing of muscle action may differ from one subject to another depending on the relative strength of the muscle involved. In light of this, inter-individual differences in coordination based CMJ PDFs (and thus CMJ PRFs) may be expected.

The time between joint reversals, peak powers and peak moments at adjacent joints have been used to quantify CMJ coordination and typical magnitudes of the former parameters are outlined in Tables 2.14 and 2.15, respectively. Magnitudes for the time between peak moment at the hip and knee and at the knee and ankle do not appear to be quantified as commonly but Jones and Caldwell (2003) found values of 70ms and 22ms, respectively. It is apparent that very few, if any, studies have examined a direct relationship between any of these coordination based parameters and CMJ jump height.

Table 2.14 Duration between joint reversals at adjacent joints in the CMJ

Author	Subjects	Time between JR at hip and knee (ms)	Time between JR at knee and ankle (ms)
Jensen and Philips (1994)	6 male	70	22
Rodacki et al. (2002)	11 male Physically active	74	45
Rodacki et al. (2001)	12 male Various sports	100	7
Clark et al. (1989)	18 female	NA	40

JR = joint reversal
Positive magnitudes indicate a proximal joint reversal before distal
Negative magnitudes indicate a distal joint reversal before proximal

Table 2.15 Duration between peak joint powers at adjacent joints in the CMJ

Author	Subjects	Time between peak power at hip and knee (ms)	Time between peak power at knee and ankle (ms)
Bobbert and Van Ingen Schenau (1988)	10 male Volleyball	110	10
Rodacki et al. (2002)	11 male Physically active	74	45
Rodacki et al. (2001)	12 male Various sports	187	23

Positive magnitudes indicate a proximal joint reversal before distal
Negative magnitudes indicate a distal joint reversal before proximal

2.3 Training interventions to increase countermovement jump ability

This section will begin with a discussion on the basic principles of enhancing CMJ jump height using neuromuscular training exercises (2.3.1). This will be followed by a brief discussion of the different training methods typically used to enhance CMJ jump height (2.3.2). The remainder of this section will then review in detail the ability of the drop jump, squat, jump squat and drop jump to stress potential CMJ PDFs and enhance CMJ jump height (2.3.3, 2.3.4, 2.3.5, 2.3.6, respectively)

2.3.1 Enhancing CMJ jump height with neuromuscular training; some basic principles

In the CMJ, as with any athletic task, performance outcome is limited by the capacity of the neuromuscular system and the technique and coordination employed by the system to carry out the task (Bobbert and Van Soest 1994). To enhance the capacity of the neuromuscular system athletes invariably use neuromuscular training exercises. In order for a component of the neuromuscular system to be enhanced it must be challenged by a training stress at a level beyond which it is accustomed (Zatsiorsky and Kraemer 2006). Such stress (or overload), if applied appropriately over the course of a training program, will lead to specific adaptation and an increase in that neuromuscular capacity (Zatsiorsky and Kraemer 2006). The reader should note that the term ‘training stress’ or ‘stress’ is used instead of ‘overload’ in this review. Some authors have established the acute training stress imposed by a given training exercise by comparing the magnitude of kinetic parameters produced in the training exercise with those produced in the task being trained (Bobbert et al. 1986; Bobbert et al. 1987a and b; Holcomb et al. 1996a). It could be suggested that such an acute pre-training stress analysis may provide an insight into the likely post-training changes that specific CMJ kinetic parameters may experience following a suitable training period (Bobbert 1990; Bobbert et al. 1986a). As far as this author is aware, the effectiveness of an acute pre-training stress analysis (at providing a pre-training insight into specific post-training changes) has yet to be tested with training interventions.

As outlined above, performance outcome in the CMJ (jump height), or in any task, is not solely determined by the neuromuscular capacity of the system but also by the technique and coordination employed (Bobbert and Van Soest 1994). Various aspects of CMJ technique and coordination have been proposed to influence CMJ jump height (see section 2.2). Bobbert et al. (1990) contend that individuals mainly improve aspects of technique and coordination by repeatedly executing the task of interest, in this case the CMJ, correctly. However, various authors have reported that training exercises traditionally employed to enhance aspects of CMJ neuromuscular capacity may also influence jumping technique and coordination (Brown et al. 1986; Hunter and Marshall 2002; Markovic et al. 2007; Toumi et al. 2004; Walsh et al. 2004). For example, Hunter and Marshall (2002) found a significant increase in CMJ eccentric stiffness (47%) and COM vertical displacement (12%) following a training program of combined heavy resistance and dynamic jumping exercises. Unfortunately the effects of various training methods on jump technique and coordination are typically left undocumented (Hunter and Marshall 2002) and thus are not well understood (Lees 2000). It could be speculated that training exercises commonly employed to enhance neuromuscular capacity may also stress various aspects of CMJ technique and coordination thereby inducing a learning effect. As an example, a training exercise with a greater eccentric stiffness or a quicker concentric phase than that of the CMJ, may induce a learning effect whereby these qualities transfer to the CMJ. It is tempting to suggest that a pre-training comparison of CMJ kinematics and the kinematics of a given training exercise may give an insight into potential post-training CMJ technique and coordination changes. This is essentially an extension of what Bobbert (1990) has suggested for kinetic parameters (see previous paragraph). The effectiveness of such a pre-training analysis in predicting post-training kinematic changes requires testing with training interventions.

It should be noted that some training induced changes in technique or coordination parameters may not be beneficial for jumping performance and in some cases may be detrimental. This is due to the fact that for many CMJ technique and coordination parameters an optimum magnitude may exist (Hunter and Marshall 2002; van Ingen Schenau 1989). A training induced deviation from this optimum may therefore be detrimental to CMJ jump height achievement. This lead Rodacki et al. (2002) to warn against repeatedly practising with an inappropriate coordination strategy as it may reinforce a coordination pattern that is not optimal for maximal performance.

Other principles of training should also be considered when attempting to enhance performance outcome (jump height) through neuromuscular training. In order for training improvements to transfer from the training exercise to the task of interest, Fowler and Lees (1998) and Zatsiorsky and Kraemer (2006) suggest that the exercise must be as close as possible to the task in terms of type of muscle action used, range of joint angles, velocity of contraction and coordination. This is known as training exercise specificity and it is suggested (Zatsiorsky and Kraemer 2006) that it becomes increasingly important as the training age of the athlete increases and as the sports season moves from pre-season to in-season. Zatsiorsky and Kraemer (2006) also highlight the need for training individualisation, which arises due to the fact that all individuals are unique in terms of their neuromuscular capacity, anthropometrics, muscle morphology and training history. These authors suggest that the use of average training routines may not be of maximal benefit to every individual, thus training individualisation will optimise results and enhance the desired adaptation.

2.3.2 Training methods to improve countermovement jump ability

To enhance maximal CMJ jumping ability various neuromuscular training methods are available to the athlete, including: traditional resistance training (e.g., squat), ballistic resistance training (e.g., jump squat), Olympic weightlifting-type training (e.g., power clean) and plyometric training (e.g., drop jump) (Kraemer and Newton 1994; Wilson et al. 1993).

Traditional resistance training involves lifting heavy loads (close to one repetition maximum load) for few repetitions at relatively slow velocities. While it has been suggested that this method of training may be well suited to enhance maximal strength (Brown et al. 1986), Kraemer and Newton (1994) argue that traditional resistance training may not have the velocity specificity of the more dynamic CMJ and thus the transfer of adaptations from resistance training to the CMJ may be limited.

Ballistic training involves traditional resistance training exercises with lighter loads (e.g. 30% 1RM) carried out in an explosive manner where the bar, or the bar and subject, are projected at the end of the movement (Wilson et al. 1993). As such, large forces and velocities are achieved throughout a greater proportion of the concentric phase and therefore this method of training is considered by some (Baker et al. 2001) to be most effective at enhancing neuromuscular power output. In addition, Wilson et al. (1993) suggest that ballistic exercises have greater training specificity to dynamic movements like the CMJ than traditional resistance training methods. In light of this, neuromuscular adaptations following ballistic training may transfer more readily to dynamic sporting movements.

Plyometric training exercises involve a rapid and forceful muscular pre-stretch before a quick and powerful concentric contraction of the same muscles (Bobbert et al. 1986a; Wilson et al. 1993). As such, these exercises exploit the stretch shortening cycle to produce large concentric forces in an explosive manner (Bobbert et al. 1987a). Plyometric training exercises are thus proposed as appropriate training exercises to enhance neuromuscular power production (Lees and Fahmi 1994) and rate of force development (Wilson et al 1996).

Olympic weightlifting exercises and their derivatives, such as the power clean, involve lifting heavy loads at high speeds and typically incorporate an explosive extension of the hip, knee and ankle joints (Kraemer and Newton 1994). As such these training exercises are becoming increasingly popular as a means of enhancing performance outcome in dynamic tasks (Kawamori and Haff 2004) such as the CMJ.

The remainder of this section (2.3) will examine the following training exercises in more detail: drop jump, squat, jump squat and power clean. The extent to which each exercise appears to acutely stress potential CMJ PDFs will be discussed, as will the results of training studies that have examined the effects of each training exercise on CMJ jump height.

2.3.3 The drop jump as a training exercise to improve countermovement jump ability

The drop jump (DJ) is a popular form of plyometric exercise commonly used to train vertical jump ability (Fowler and Lees 1998). It involves stepping from a prescribed height and, upon landing, jumping vertically as maximally and as explosively as possible (Bobbert et al. 1987a; Fowler and Lees 1998) [Figure 2.5]. Drop jumping requires a high intensity eccentric contraction of the leg extensor muscles followed by a rapid and powerful concentric contraction. In light of this the DJ has the potential to stimulate a greater SSC utilisation than the CMJ, which should in turn facilitate a greater concentric neuromuscular output. The DJ therefore has the capacity to stress numerous potential CMJ PDFs but is considered to be particularly effective at enhancing lower extremity power production and rate of force development (Holcomb et al. 1996b; Lees and Fahmi 1994; Wilson et al. 1996).

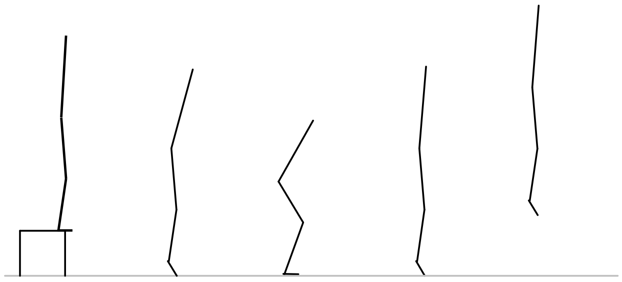

Figure 2.5 A graphical representation of the drop jump

2.3.3.1 The acute training stress experienced by potential CMJ PDFs in the drop jump

Comparing the magnitudes of kinetic and kinematic parameters in the DJ relative to the CMJ may give an indication of the acute training stress experienced by these parameters in the DJ. Such an analysis may in turn provide an insight into the ability of the DJ to enhance these parameters and thus CMJ jump height if, of course, the parameters in question are true CMJ PDFs. Maarten F. Bobbert and colleagues from the Free University in Amsterdam have carried out the most extensive comparisons of kinetic and kinematic parameters in the DJ and CMJ. These authors have primarily focused on the influence of (a) DJ technique, and (b) drop height, on the training stress imposed by a DJ. In light of this, the following review of the ability of the DJ to acutely stress potential CMJ PDFs will be discussed under these subheadings.

(a) The effect of DJ technique on the acute training stress experienced by potential CMJ PDFs

Bobbert et al. (1986a) noticed that when subjects were asked to DJ (from 40cm) there appeared to be a jump technique continuum between fast, small amplitude DJs, and slow, large amplitude DJs. The authors realised that these inter-individual technique differences led to inter-individual differences in the stress imposed by the DJ. Such inter-individual training stress differences would have been masked if all individuals were combined in one main group. The main group was thus divided into two homogenous subgroups: the bounce drop jump (BDJ) group and the countermovement drop jump (CDJ) group. The BDJ group produced jumps utilising smaller COM amplitudes with concentric phase durations of less than 200ms. The CDJ group produced jumps with larger COM amplitudes and greater concentric phase durations (>260ms). The choice of jumping strategy appeared arbitrary and not due to differences in anthropometrics (Bobbert et al. 1986a). A comparison of the whole body kinetics and kinematics of the CMJ and the DJ produced by both the CDJ and the BDJ group is provided in Table 2.16 while a comparison of the joint level kinetics and kinematics is provided in Table 2.17.

Table 2.16 A comparison of whole body kinetics and kinematics in the CMJ and DJ for both the 'counter' group and the 'bounce' group (Bobbert et al. 1986a)

	Counter group		Bounce group	
	CMJ	DJ	CMJ	DJ
COM amplitude [from standing to the low point of the COM] (cm)	35	33	33	21 *
Eccentric phase duration (ms)	Not provided	230	Not provided	143
Concentric phase duration (ms)	280	280	280	170 *
Force at start of the concentric phase ($N.kg^{-1}$)	23.6	25.5	21.2	40.2 *
Concentric work done ($J.kg^{-1}$)	7.9	7.4	6.7	5.7 *

* Significantly different ($p < 0.05$) compared to the CMJ

Table 2.17 A comparison of joint kinetics and kinematics in the CMJ and DJ for both the ‘counter’ group and the ‘bounce’ group (Bobbert et al. 1986)

		Counter group		Bounce group	
		CMJ	DJ	CMJ	DJ
Angle at joint reversal (deg)	Hip	69.3	79.1	82.5	118.0 *
	Knee	76.8	75.6	84.8	100.8 *
	Ankle	76.8	79.6 *	74.5	75.6
Moment at joint reversal ($Nm.kg^{-1}$)	Hip	4.5	4.6	3.5	3.6
	Knee	3.3	4.1	3.0	5.4 *
	Ankle	3.1	3.3	2.5	5.5 *
Concentric peak moment ($Nm.kg^{-1}$)	Hip	4.8	4.8	4.5	4.0
	Knee	3.7	4.4	3.6	5.5 *
	Ankle	3.5	3.7	3.2	5.8 *
Concentric peak power ($W.kg^{-1}$)	Hip	20.4	17.6	18.5	15.8
	Knee	21.8	23.2	19.5	25.5 *
	Ankle	24.8	23.4	24.1	31.9
Concentric work done ($J.kg^{-1}$)	Hip	3.1	2.5 *	2.5	1.1 *
	Knee	2.5	2.8	2.1	1.9
	Ankle	2.3	2.1	2.1	2.7 *

* Significantly different ($p < 0.05$) compared to the CMJ

Concentric kinetic parameter magnitudes produced in the CDJ were never significantly ($p<0.05$) greater than those produced in the CMJ (Tables 2.16 and 2.17). In contrast, knee and ankle concentric peak moment and knee concentric peak power were significantly greater in the BDJ in comparison to the CMJ. In light of these findings, Bobbert et al. (1986a) contended that knee and ankle concentric peak moment and knee concentric peak power experienced an appropriate training stress in the BDJ. The authors suggest that such a training stress over the course of a training period may be expected to lead to an enhancement in these capacities. Bobbert et al. (1986a) also theorise that the larger ankle and knee moments and powers in the BDJ compared to the CMJ were due to a greater SSC utilisation in the former. This, the authors suggest, was evidenced by the fact that both ankle and knee moments at joint reversal were significantly greater in the BDJ than in the CMJ; a greater moment at joint reversal is thought to be an indicator of greater SSC utilisation (Bobbert et al. 1986a). Eccentric loading in the CDJ on the other hand may not have been of a large enough intensity to stimulate effective SSC utilisation (Bobbert et al. 1986a). This is evidenced by the fact that ankle and knee moments at joint reversal were not significantly greater in the CDJ than in the CMJ.

Table 2.16 and 2.17 also detail the acute training stress experienced by the two different DJ groups in selected CMJ kinematic parameters. The authors found that for those who utilised a BDJ, COM amplitude, hip and knee maximum flexion angle and concentric phase duration were all significantly smaller in the DJ compared to the CMJ. If those individuals carried out a period of BDJ training, it is not inconceivable that a learning effect may occur whereby a CMJ produced post-training may exhibit some of these BDJ characteristics. For the CDJ group on the other hand, post training changes in COM amplitude, peak hip and knee flexion angle and concentric phase duration would not be expected as there was no acute training stress in place (Tables 2.16 and 2.17).

In a follow up study, Bobbert et al. (1987a) instructed a group of individuals to produce either a CDJ or BDJ. A comparison of the whole body kinetics and kinematics produced in a CMJ, CDJ and BDJ is provided in Table 2.18, while a comparison of joint level kinetics and kinematics is provided in Table 2.19. The COM amplitude and time durations of the eccentric and concentric phases for the CDJ were shorter than those reported by Bobbert et al. (1986a). In fact, the duration of the CDJ in Bobbert et al. (1987a) [210ms] approached the criteria for a BDJ [<200ms] set out by Bobbert et al. (1986a). As such, the CDJ produced by the subjects in Bobbert et al. (1987a) could be viewed as a larger amplitude BDJ. Possible reasons for these differences include the shorter drop height (20cm) and more skilled jumpers (5cm better on average in a CMJ) used in the study by Bobbert et al. (1987a) compared to the previous study. It is apparent, based on these observations, that more than two DJ techniques are likely to exist and that a simple classification of a DJ as either being a BDJ or a CDJ may not be appropriate.

Table 2.18 A comparison of whole body kinetics and kinematics in a CMJ, BDJ and CDJ (Bobbert et al. 1987a)

	CMJ	CDJ	BDJ
COM amplitude (cm)	37	25 *	13 * †
Eccentric phase duration (ms)	550	190 *	130 * †
Concentric phase duration (ms)	290	210 *	130 * †
Force at start of the concentric phase (N.kg^{-1})	23.7	30.8 *	47.3 * †

CDJ = countermovement drop jump; BDJ = bounce drop jump

* Significantly different ($p < 0.05$) compared to the CMJ

† Significantly different ($p < 0.05$) compared to the CDJ

Table 2.19 A comparison of joint kinetics and kinematics in a CMJ, CDJ and BDJ (Bobbert et al. 1987a)

		CMJ	CDJ	BDJ
Angle at joint reversal (deg)	Hip	70.5	99.7 *	131.2 * †
	Knee	80.2	86.5 *	110.6 * †
	Ankle	70.5	71.6	72.2
Moment at joint reversal (Nm.kg^{-1})	Hip	4.8	3.8	3.4 *
	Knee	3.7	5.6 *	6.4 * †
	Ankle	3.1	4.1 *	6.9 * †
Concentric peak moment (Nm.kg^{-1})	Hip	5.0	4.3 *	3.7 * †
	Knee	4.3	5.8 *	6.6 * †
	Ankle	3.7	4.3 *	7.1 * †
Concentric peak power (W.kg^{-1})	Hip	18.0	14.8	13.7
	Knee	30.1	32.0	35.4 * †
	Ankle	28.9	29.3	53.4 * †

* Significantly different ($p < 0.05$) compared to the CMJ

† Significantly different ($p < 0.05$) compared to the CDJ

In the study by Bobbert et al. (1987a) knee and ankle peak moments were greater in both forms of DJ compared to the CMJ, but were greater in the BDJ compared to the CDJ. Moreover, knee and ankle concentric peak power was greater in the BDJ than the CMJ, while there were no significant differences between these power outputs in the CMJ and CDJ. These findings led the authors to suggest that the BDJ was better suited than the CDJ to produce a training stimulus that would allow the knee extensors and plantar flexors to deliver more force and power (Bobbert et al. 1987a). COM amplitude, eccentric and concentric phase durations and maximum knee and hip flexion angles were significantly smaller in both forms of DJ compared to the CMJ, but were significantly smaller in the BDJ compared to the CDJ. Based on these findings it could be speculated that both forms of DJ may induce learning effects whereby a CMJ produced post-training would exhibit some of these DJ characteristics. These post-training changes would be expected to be more notable following BDJ training in comparison to CDJ training, due to the greater magnitude of training stress in the former.

Of interest, both Bobbert et al. (1986a) and Bobbert et al. (1987a) found that the DJ, regardless of the technique used, did not acutely stress any of the hip kinetic parameters detailed (Tables 2.17 and 2.19). Based on these findings it is the opinion of this author that individuals with predominantly hip related CMJ PDFs may not experience a notable increase in CMJ jump height following DJ training.

Due to the large amount of eccentric loading involved in drop jumping the DJ has the potential to stress numerous eccentric parameters that may well be CMJ PDFs. Unfortunately the majority of kinetic parameters detailed in both of the studies outlined above were concentric phase parameters (Bobbert et al. 1986a; Bobbert et al. 1987a). Force and joint moments at joint reversal were however provided and these parameters may give an insight into the eccentric loading that preceded the instant of joint reversal. Based on the magnitudes of these parameters in the CMJ and DJ (Tables 2.16 and 2.19) it seems that the DJ has the potential to produce a greater eccentric neuromuscular output than the CMJ, and thus may acutely stress several CMJ eccentric parameters. Similar to that discussed above, the magnitude of this training stress may depend on the type of DJ technique employed. Bobbert et al. (1987a) found that whole body force and knee and ankle joint moments at joint reversal were significantly greater in the DJ than in the CMJ, but were significantly greater in the BDJ than in the CDJ (Tables 2.18 and 2.19). Moran and Wallace (2007) provided additional evidence supporting the potential of the DJ to induce an acute stress of CMJ eccentric neuromuscular output. They found hip, knee and ankle eccentric work done was significantly greater in a DJ with a 70º knee flexion angle than in a CMJ with the same magnitude of knee flexion (Table 2.20)

Table 2.20 A comparison of joint eccentric work done in a CMJ and DJ (Moran and Wallace 2007)

		CMJ ‡	DJ ‡
Eccentric work done ($J.kg^{-1}$)	Hip	0.31	0.92 *
	Knee	0.79	1.72 *
	Ankle	0.26	1.60 *

‡ Countermovement was controlled to 70° knee bend
* Significant difference between CMJ and DJ ($p<0.05$)

The findings of the studies outlined above highlight that the DJ has the ability to stress potential CMJ PDFs, but that the presence or absence of a training stress depends on how an individual actually carries out the DJ (Bobbert et al. 1987a). Coaches have therefore been advised to exert a greater control over their athlete's drop jumping technique (Bobbert 1990). Several studies have demonstrated that the instructions given to individuals while carrying out drop jumps can in part influence the technique utilised (Holcomb et al. 1996a; Young et al. 1995; Young et al. 1999). Young et al. (1995) demonstrated that an instruction to perform a DJ for 'maximal height' produced a DJ with a significantly longer contact time (35ms longer on average) than a DJ for 'maximal height and minimal contact time' (Young et al. 1995). However, even if a group of individuals are issued with the same drop jumping instructions there is still likely to be some degree of inter-subject variability in terms of how a DJ is produced, and thus, the extent to which the DJ stresses potential CMJ PDFs. This is in accordance with the notion that every individual is unique and may thus possess an individualised neuromusculoskeletal solution for a given task (Bates 1996; Dufek et al. 1995). Such uniqueness is likely due to inter-individual differences in neuromuscular capacity (e.g. ability to tolerate eccentric loads, joint dominance), anthropometrics (e.g. limb lengths), muscle morphology (e.g. percentage muscle fiber type), technique preference and past-training experience. Kolias et al. (2004) for example, found that when elite athletes from different sporting backgrounds were instructed to carry out a DJ with the instruction to jump 'as high as you can and as fast as you can'; the groups produced different drop jumping techniques and neuromuscular outputs. The amplitude of COM movement utilised by track and field athletes (34.2cm) was significantly less than that utilised by soccer players (51.8cm), volleyball players (43.6cm), handball players (53.0cm) and basketball players (52.7cm), while peak concentric power produced by the track and field athletes (47.2W.kg^{-1}) was significantly greater (by 12.7W.kg^{-1} on average) than that produced by the other respective athlete groups (Kolias et al. 2004). In addition, Viitasalo et al. (1998) found that triple jumpers initiated activation of their lower extremity muscles before touchdown earlier and to a greater extent than physically active controls. This muscular pre activity is thought to play a key role in eccentric leg stiffness regulation, an ability which facilitates better SSC utilisation (Viitasalo et al. 1998). This and other between group differences in neuromuscular functioning in the DJ were hypothesised to be due to different training backgrounds and/or different inherited abilities, such as muscle fiber type distribution (Viitasalo et al. 1998). In summary, how an individual carries out a DJ appears to affect the acute training stress imposed. Given that each individual is unique, it can be suggested that different individuals have the capacity to experience different training stresses in the DJ. Such a hypothesis requires testing both acutely and with training interventions.

(b) The effect of drop height on the acute training stress experienced by potential CMJ PDFs

A faster and more forceful eccentric contraction in a SSC movement is expected to allow greater SSC utilisation and an enhancement in concentric neuromuscular output (Bobbert et al. 1987b). Increasing the drop height of a DJ may facilitate such conditions, as the COM would be travelling at a greater downward velocity requiring greater eccentric forces to decelerate it. It is tempting to suggest therefore that DJs from higher heights will lead to a greater neuromuscular output and thus increase the DJs ability to stress the neuromuscular system (Bobbert et al. 1987b). As outlined below however, different authors have shown that there is a limit beyond which further increases in drop height do not facilitate greater concentric neuromuscular outputs (Asmussen and Bonde-Petersen 1974; Bobbert et al. 1987b; Lees and Fahmi 1994; Walsh et al. 2004).

Lees and Fahmi (1994) examined the effect of changes in drop height from 0cm (CMJ) to 68cm on various parameters including jump height, whole body concentric peak power and COM amplitude (Table 2.21). As drop height increased from 0cm (CMJ) to 12cm both jumping height and concentric peak power output were enhanced but as drop heights increased beyond 12cm these variables experienced declines. Conversely, the amplitude of the COM initially decreased with an increase in drop height but then increased steadily with further increases in drop height (Table 2.21). In light of these results the authors concluded that a drop height of 12cm was optimal for the subjects used. At greater heights, particularly over 36cm, the subjects altered their technique by using larger movement amplitudes, which Lees and Fahmi (1994) suggest was in order to protect the body from the larger impact loads associated with higher drop heights. As a result of these technique changes the ability to recover the greater potential energy from higher drop heights was lost (Lees and Fahmi 1994). Bobbert et al. (1987b) also suggested that no notable benefit could be derived from drop jumping at heights beyond a certain level. They found that as drop heights increased from 20cm to 60cm there was no significant increase in concentric neuromuscular output (Tables 2.22 and 2.23) (Bobbert et al. 1987b).

Table 2.21 Jump height, whole body concentric peak power and COM amplitude during DJs from various starting heights (Lees and Fahmi 1994)

Drop height (cm)	Jump height (cm)	Whole body concentric peak power (W.kg-1)	COM amplitude
0 (CMJ)	32.8	42.0	34.1
12	39.2	48.1	30.2
24	34.2	46.2	37.5
36	31.4	45.0	43.4
46	33.0	41.5	50.9
58	30.8	40.0	56.1
68	26.1	36.7	59.8

Table 2.22 A comparison of whole body kinetics and kinematics in DJs from 20cm, 40cm and 60 cm (Bobbert et al. 1987b)

	DJ20	DJ40	DJ60
COM amplitude (cm)	21	18 *	21 †
Eccentric phase duration (ms)	170	140	150
Concentric phase duration (ms)	180	160	190 †
Whole body eccentric work done (J.kg^{-1})	3.3	4.6 *	6.2 † *
Whole body concentric work done (J.kg^{-1})	5.1	5.3	5.2
Force at start of the concentric phase (N.kg^{-1})	32.4	39.4	32.7

* Significantly different ($p < 0.05$) compared to DJ20

† Significantly different ($p < 0.05$) compared to DJ40

Table 2.23 A comparison of joint kinetics and kinematics in DJs from 20cm, 40cm and 60 cm (Bobbert et al. 1987b)

		DJ20	DJ40	DJ60
Angle at joint reversal (deg)	Hip	116.3	121.5	114.6
	Knee	95.1	100.8	95.7 †
	Ankle	72.2	74.5	76.8
Eccentric peak moment (Nm.kg^{-1})	Hip	4.0	4.2	4.6
	Knee	5.1	6.1 *	6.5
	Ankle	4.3	5.2	5.5 *
Moment at joint reversal (Nm.kg^{-1})	Hip	3.0	3.2	3.4
	Knee	5.0	5.8	5.2
	Ankle	4.2	5.0	4.1
Concentric peak moment (Nm.kg^{-1})	Hip	3.4	3.3	3.7
	Knee	5.1	5.9	5.2
	Ankle	4.2	5.2	4.5 †
Concentric peak power (W.kg^{-1})	Hip	12.1	15.0	13.5
	Knee	25.6	30.2	24.7
	Ankle	23.3	29.2	26.8 †

* Significantly different ($p < 0.05$) compared to DJ20

† Significantly different ($p < 0.05$) compared to DJ40

Different individuals may have the capacity to produce different variants of DJ, even when drop jumping from the same drop height. This is based on the notion, already outlined previously, that each individual is unique and may possess an individualised neuromusculoskeletal solution for a given task (Bates 1996; Dufek et al. 1995). For example, Viitasalo et al. (1998) observed no notable changes in ankle and knee angular displacement at higher drop heights (40cm versus 80cm) for triple jumpers, while physically active controls produced significantly larger ankle and knee displacements at the higher heights. It is reasonable to suggest therefore that an ‘optimal’ drop height is likely to vary from individual to individual. Nevertheless Lees and Fahmi (1994) suggest that optimal drop heights for drop jumping are more likely to be at lower rather than higher drop heights (Lees and Fahmi 1994).

2.3.3.2 The effect of drop jump training on potential CMJ PDFs

The previous section (2.3.3.1) established that the DJ has the ability to acutely stress certain CMJ kinetic and kinematic parameters that are potential CMJ PDFs. This was established by comparing parameter magnitudes in the CMJ with those in the DJ. More compelling evidence of the presence of acute training stress can be obtained by identifying the post-training magnitude changes in CMJ parameters following DJ training. Unfortunately, the majority of training studies only report post-training changes in the performance outcome of interest, in this case CMJ jump height. Indeed, as far as this author is aware, the only CMJ kinetic parameter that has been examined for post-training changes following DJ training is whole body concentric peak power. Holcomb et al. (1996b) reported a significant 6.5% increase in CMJ whole body concentric peak power following eight weeks of DJ training. This finding suggests that the DJ overloaded neuromuscular power production capacity leading to an improved power output in the CMJ. Potteiger et al. (1999) and Leubbers et al. (2003) also found statistically significant increases in CMJ peak power (3.0% and 2.7% respectively) but their training programs consisted of a combination of DJ, CMJ, standing long jump and bounding exercises. Interestingly, each of the three studies outlined also reported a significant post-training increase in CMJ jump height. It could be speculated therefore that whole body peak power output may be a likely CMJ PDF.

The reporting of post-training magnitude changes in CMJ technique and coordination parameters following DJ training is rarely undertaken (Hunter and Marshall 2002). Hunter and Marshall (2002) did however report a significant increase in CMJ eccentric stiffness (47%) and COM vertical displacement (12%)

following a ten-week training program that included DJ training (along with squatting, deadlifting and both weighted and unweighted CMJs).

2.3.3.3 The effect of drop jump training on countermovement jump ability

Bobbert (1990) reviewed 15 different training studies that examined the effects DJ training on vertical jump ability. The authors concluded that while the DJ appeared to be effective at improving jumping ability in general, there were instances where no notable post-training enhancements occurred. Moreover, the extent to which vertical jump ability increased following training varied considerably across studies (1.8cm-10.2cm) (Bobbert 1990).

The current review presents the details of five DJ training studies (only one of which was included in the review of Bobbert (1990)) and their effects on CMJ jump height (Table 2.24). Three of the five studies presented found significant increases in CMJ jump height following training (Gehri et al. 1998; Matavulj et al. 2001; Wilson et al. 1996) while two did not (Brown et al. 1986; Young et al. 1999). Additionally, the three studies that reported a post-training improvement in CMJ jump height report substantially different percentage improvements ranging from 8-18% (Gehri et al. 1998; Matavulj et al. 2001; Wilson et al. 1996). It would appear (based on the information provided in Table 2.24) that there are no obvious differences in training program design factors (duration, frequency, drop height used) that may readily explain the inconsistent effects of DJ training on vertical jump height (Table 2.24). For example, Matavulj et al. (2001) found a significant increase in CMJ jump height (13% on average) following just 6 weeks of DJ training three times a week, with an average of 30 jumps per session. Young et al. (1999) employed a similar program duration, frequency and number of jumps per session (24-30 jumps) but found no increase in CMJ jump height.

Table 2.24 The effect of drop jump training on CMJ jump height

Study	Subjects	Drop jump training	Drop Height (cm)	CMJ change (cm)	Percentage change	Statistical significance
Brown et al. (1986)	13 male Basketball	12 weeks 3d.wk^{-1} 3 X 10 reps	45	5.5 (11%)	11%	No*
Gehri et al. (1998)	11 male Physically active	10 weeks 2d.wk^{-1} 4 X 8 reps	40	2.1 ± 1.9 (8%)	8%	Yes
Matavulj et al. (2001)	22 male Basketball	6 weeks 3d.wk^{-1} 3 X 10 reps	Group (a): 50 Group (b): 100	Group (a): 4.8 (~13%) Group (b): 5.6 (~13%)	(a) 13% (b) 13%	Yes
Wilson et al. (1996)	14 male Weight trained	8 weeks 2d.wk^{-1} 4-6 X 8 reps	20-70cm	10.4 (18%)	18%	Yes
Young et al. (1999)	16 male Sport with jump	6 weeks 3d.wk^{-1} 4-5 X 6 reps **	~30cm **	Group (a): 0.9 (1.8%) Group (b): -0.4 (0%)	(a) 1.8% (b) 0%	No

* CMJ with no arm swing was not significantly enhanced but CMJ with arm swing was

** Group a: DJ for maximal height at a drop height that allowed maximal jump heights
Group b: DJ for both maximal height and minimum contact time at a drop height that facilitated this

De Villarreal et al. (2009), in a review of several plyometric training studies, found a trend toward greater enhancements in jumping ability following plyometric training in better trained rather than less well trained individuals. While this appears to go against general training theory, the authors suggest that plyometric training requires appropriate technical ability as well as optimal levels of muscle strength and coordination (De Villarreal et al. 2009), which would be found in more well trained jumpers. This trend is not however apparent in Table 2.24 as Wilson et al. (1996) found very large increases in CMJ jump height (10.4cm) in a group of individuals with no jump training experience.

Finally, it also appears that the inconsistent training effects of DJ training cannot be fully explained by differences in DJ instruction. Young et al. (1999) instructed one DJ training group to DJ for maximal jump height (CDJ style jump) while another was instructed to jump for maximal height while minimising ground contact time (BDJ style jump). There was no between group differences in jump height change following training, as outlined in Table 2.24.

It has been suggested in section 2.3.3.1 that regardless of the drop jump instruction given, or the drop height used, individuals have the potential to carry out a DJ in different ways due to inter-individual differences in neuromuscular capacity, anthropometrics, muscle morphology and individual preference. Thus, the training stress imposed by a DJ has the potential to vary between individuals (and thus groups). This may in part explain the variance in post-training CMJ jump height change that is observable in the studies outlined in Table 2.24. In addition, section 2.2 provided evidence to suggest that different individuals have the potential to possess different CMJ PDFs. This may also, in part, explain why the DJ may be effective at enhancing some individual's CMJ jump height but is not as effective at doing so for other individuals. These respective hypotheses require more direct examination with a research study.

2.3.4 The squat as a training exercise to improve countermovement jump ability

The squat exercise is undertaken with a weighted barbell, which rests on the back across the shoulders. The weight is lowered by flexion at the hip, knee and ankle and then raised by extending these same joints (Figure 2.6). The maximal load that can be lifted for one repetition (1RM) is typically used to test an individual's maximal strength. Percentages of this 1RM load are employed in squat training programs. Traditionally, squat training to enhance CMJ jump height involves lifting heavy loads (80-90% 1RM) at relatively slow velocities (Hoffman et al. 2004; Wilson et al. 1995). This method of resistance training is suggested to be optimal for enhancing lower extremity strength (force production capacity) [Crewther et al. 2005].

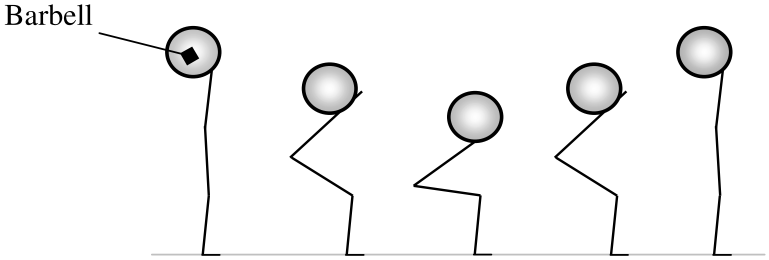

Figure 2.6 A graphical representation of the squat

Some authors have questioned the use of heavy weight squat training as a means of enhancing CMJ jump height (Baker 1996; Stone et al. 2003; Weiss et al. 2000). One of the main criticisms of the squat is that it is carried out relatively slowly and thus lacks the velocity specificity of the more dynamic CMJ (Young and Bilby 1993). It is suggested that slow movements like a squat primarily recruit and adapt slow twitch fibers while more dynamic movements like the CMJ utilise fast twitch fibers (Young and Bilby 1993). However, authors like Wilson et al. (1993) and Young and Bilby (1993) theorise that fast twitch fibers can be recruited in the squat as long as heavy loads are used and there is an intention to lift the load as quickly as possible (Wilson et al. 1993; Young and Bilby 1993).

Another criticism of using heavy load squat training to enhance CMJ jump height is that the neuromuscular capacity it predominantly enhances, the ability to produce large forces, may not in fact be a CMJ PDF. Dowling and Vamos (1993) suggest that while high peak forces may be required for good jumps, they are not necessarily indicative of better jumps. Indeed Baker (1996) suggests that athletes with an already well developed lower extremity strength may not experience notable increases in CMJ jump height following lengthy periods of strength training even if significant improvements in 1RM occur.

Despite the criticisms of the squat outlined above it is still commonly employed by athletes to enhance their CMJ jump height. Moreover, as apparent from Table 2.30 to follow, it has been found to be effective at improving CMJ jump height on a number of occasions.

2.3.4.1 The acute training stress experienced by potential CMJ PDFs in the squat

As far as this author is aware no studies have directly compared the magnitudes of kinetic and kinematic parameters in the CMJ relative to the squat. A review of a number of studies that have detailed squat kinetics and kinematics (below) suggests that while the squat has the potential to stress and thus enhance likely CMJ PDFs, the training stress imposed may have the potential to vary from individual to individual.

Rahmani et al. (2001) showed that peak whole body force in a squat increases as the weight lifted increases. Subjects squatting with a 60kg load produced a peak concentric force of 32.9N.kg^{-1}, which increased to 37.9N.kg^{-1} when lifting 120kg and 43.3N.kg^{-1} when lifting 180kg. Comparing these values to the range of peak forces obtained in several studies of the CMJ (21.0–24.7 N.kg^{-1}, Table 2.2) clearly suggests the ability of the squat to stress peak force generating capacity in the CMJ.

Peak concentric joint moments produced during a squat, and thus the training stresses imposed on the neuromuscular system, show much inter-individual variation depending on the squatting technique employed. Fry et al. (2003) compared hip and knee peak moments produced during an unrestricted squat where the knees were allowed to travel anterior to the toes, versus a restricted squat, where they were not. A significantly greater hip moment was found in the restricted squat (302.7Nm) compared to the unrestricted squat (28.2Nm). Conversely, a significantly greater knee moment was found in the unrestricted squat (150.1Nm) compared to the restricted squat (117.3Nm).

The position of the barbell on the back while squatting also affects peak knee and hip moments (Wretenberg et al. 1996). Bar placement can be generally classified as either ‘high bar’ (just below C7, across the shoulders) or ‘low bar’ (further down the back across the spine of scapula) [Wretenberg et al. 1996]. In practise athletes may use a bar placement that is not strictly defined, but it is clear from the findings of Wretenberg et al. (1996) that bar placement can effect maximal knee and hip moments in a squat (Table 2.25). In this study hip and knee moments produced by power lifters (low bar technique) were compared to those of weightlifters (high bar technique) with both groups lifting a 65% 1RM load. In addition, moments produced at different squatting depths (deep squat versus a parallel squat) were also analysed (Table 2.25). The low bar squatting technique is characterised by a greater hip flexion than the high bar technique. This results in the creation of a larger hip moment arm but a shorter knee moment arm in comparison to the high bar technique. This explains the significantly larger hip moments (~26%) and smaller knee moments (~45%) in the low bar versus high bar technique (Table 2.25). The high bar technique is characterised by a more upright posture with moments at the hip and knee more equally distributed than that observed in the low bar technique (Table 2.25). Even though individuals using the low bar technique lifted heavier loads than those using the high bar technique, peak moments at the knee were significantly larger (45% larger) in the latter group.

A deeper squat does not appear to alter the hip moment produced but does tend to result in an increase in knee peak moment (Table 2.25). For example, those utilising a low bar technique experienced a significant 45% increase in peak knee moment in a deep squat in comparison to a parallel squat (Wretenberg et al. 1996). In general, the peak moment values presented in Table 2.25 are not greater than the peak moment values typically found in the CMJ (Table 2.5, pg17). However, moment values would be expected to increase with an increase in load. The load used in this study, 65% 1RM, is lower than that usually used to train CMJ jump height (80-90% 1RM).

Table 2.25 A comparison of hip and knee moments and angles in high bar versus low bar, and deep versus shallow, squats (Wretenberg et al. 1996)

	Powerlifters (low bar technique)		Weightlifters (high bar technique)	
	Parallel squat	Deep squat	Parallel squat	Deep Squat
Peak hip moment ($Nm.kg^{-1}$)	3.6*	3.7*	2.6	2.8
Peak knee moment ($Nm.kg^{-1}$)	1.1 * †	1.6	1.6	2.3
Hip angle at low point (degrees)	48*	34*	69	55
Knee angle at low point (degrees)	69	54	64	42

* Significant difference low bar versus high bar
† Significant difference parallel versus deep squat

Due to the large eccentric loading involved in the squat it could be theorised that squat training will stress eccentric CMJ parameters that are potential CMJ PDFs. Escamilla et al. (2001) detailed eccentric joint moments in squats of various stance widths (narrow, medium and wide stance) at the instant when the knee was at 90° of flexion (Table 2.26). Hip eccentric moments in the squat in this study (~5.2$Nm.kg^{-1}$) did not appear to vary across stance widths (Table 2.26) and are larger than peak hip eccentric moments typically produced in the CMJ (~4.3$Nm.kg^{-1}$, Table 2.12). Similarly, knee eccentric moments in the squat (~6.7 $Nm.kg^{-1}$, Table 2.26) were in general larger than eccentric peak knee moments typically found in the CMJ (~4.2$Nm.kg^{-1}$, Table 2.12). In contrast, ankle eccentric moments in the squat (~1.3 $Nm.kg^{-1}$, Table 2.26) were less than those generally reported for the CMJ (~2.7$Nm.kg^{-1}$, Table 2.12). These findings suggest that squat training with heavy loads produces larger eccentric hip and knee moments than that produced in the CMJ. Appropriate squat training could therefore lead to an enhancement of these parameters in the CMJ, which may lead to larger CMJ jump heights if, of course, these parameters were true CMJ PDFs.

Table 2.26 A comparison of eccentric joint moments produced in squats of varying stance widths (Escamilla et al. 2001)

	Narrow stance	Medium stance	Wide stance
Hip moment ‡ (Nm.kg^{-1})	5.2	5.4	5.3
Knee moment ‡ (Nm.kg^{-1})	5.7	6.6	7.9
Ankle moment ‡ (Nm.kg^{-1})	0.4	0.8*	2.8*

‡ At ninety degrees of knee flexion
* Significantly greater than narrow stance

It has been theorised throughout this review that training exercises may induce changes in CMJ technique and coordination parameters. More specifically, a prolonged period of squat training may induce a learning effect whereby some of the characteristics of the squat (detailed below) might transfer to the CMJ. Squat eccentric and concentric phase times found in previous studies are detailed in Table 2.27. Not surprisingly, due to the slow nature of lifting heavy loads, both eccentric and concentric phase times in the squat are much longer than in the CMJ. Eccentric phase times in the squat are on average three times longer than a CMJ, while concentric phase times are close to five times longer (see Table 2.13 and Table 2.9 for typical CMJ eccentric and concentric phase durations, respectively).

Typical joint flexion angles at joint reversal in the squat are detailed in Table 2.28 (larger values indicate a more extended joint, while smaller values indicate a more flexed joint). Hip flexion angles produced in the squat are typically 63.7° (Table 2.28), however Wretenberg et al. (1996) demonstrated that individuals utilising a low bar squatting technique employed a greater hip joint range of motion (hip angle of 48° at joint reversal, see Table 2.25). Typical maximal hip angles in the CMJ are ~68.7° thus the squat, particularly the low bar squat, appears to employ a greater hip range of motion than the CMJ. Similarly, the squat typically employs a greater knee joint range of motion (maximal flexion angle of ~72.5°, Table 2.28) than the CMJ (maximal flexion angle of ~80.1°, Table 2.10). In contrast, the ankle appears to undergo more flexion in the CMJ than in the squat with typical ankle angles at joint reversal in these respective exercises of ~76.6° (Table 2.10) and ~93° (Table 2.28).

Table 2.27 Squat eccentric and concentric phase durations

Authors	Eccentric phase time (ms)	Concentric phase time (ms)
Escamilla et al. (2001b)	1740	1560
Zink et al. (2001)	1710	1500

Table 2.28 Squat joint flexion angles at joint reversal

Author	Flexion angle at joint reversal (degrees)	
Escamilla et al. (2001a)*	Hip	-
	Knee	78.0
	Ankle	-
Fry et al. (2003) [restricted squat]	Hip	60.6
	Knee	73.4
	Ankle	96.0
Fry et al. (2003) [unrestricted squat]	Hip	66.7
	Knee	66.1
	Ankle	90.0

* Medium stance width value
Larger values indicate a more extended joint

2.3.4.2 The effect of squat training on potential CMJ PDFs

Morrisey et al. (1998) examined the training effects of two squats with different tempos (slow and fast) on several CMJ parameters. Interestingly, a joint specific response to training was observed. The authors found that the slow squat group's training effects were superior to the fast squat group's at the knee, while training effects at the ankle and hip were superior in the fast group. CMJ concentric average knee moment improved significantly ($p<0.05$) by ~150% in the slow group following seven weeks of training, while a significant change was not observed for the fast group. Conversely, while CMJ concentric average hip moment did improve significantly by ~30% in the slow group, a more notable increase of ~50% was observed in the fast group. In an attempt to explain these different training outcomes the authors examined the average hip and knee moments produced by both groups in the squat but surprisingly found no significant differences between them (Morrisey et al. 1998). The authors however did not compare the moments produced at the hip and knee in both squats versus those produced in the CMJ (the acute stress experienced by these parameters in the squat). Perhaps the slow group were experiencing a greater training stress at the knee by virtue of the fact that they had lower initial CMJ knee moments than the fast group. In practise different individuals are likely to train with squats of different tempos. In light of what has been discussed above, this may lead to inter-individual differences in the effects of squat training on certain CMJ parameters.

Morrissey et al. (1998) also found significant increases in CMJ concentric rate of force development, concentric peak power and concentric average power in both fast squat and slow squat training groups following the seven weeks of training (Table 2.29). While the acute training stress experienced by these CMJ parameters in both squats was not detailed, it is unlikely that they would have been found to be acutely stressed in either squat. This is due to the slow nature of both the fast and slow squat in comparison to the more dynamic CMJ. It may be surprising therefore that maximal and average concentric power and concentric rate of force development enhanced following squat training. However, squat training is likely to induce enhancements in strength and a stronger lower extremity will be able to lift a given load, in this case body weight, more quickly (Stone et al. 2003) and thus with a greater rate of force development and power.

Table 2.29 Percentage post-training changes in CMJ parameter magnitudes following squat training (Morrisey et al. 1998)

	Percentage post-training change	
	Slow squat group	Fast squat group
Concentric rate of force development	59 ± 28	62 ± 27
Concentric peak power	10 ± 10	9 ± 5
Concentric average power	35 ± 15	30 ± 9

2.3.4.3 The effect of squat training on countermovement jump ability

The details of six training studies that examined the effects of heavy squat training on CMJ jump height are detailed in Table 2.30. Of the six studies presented, three found statistically significant post-training improvements in jump height (Adams et al. 1992; Wilson et al. 1993; Wilson et al. 1996), two found no notable changes (Weiss et al. 1999; Weiss et al. 2000) while another study found a statistically significant improvement for one training group (fast squat) but not for another (slow squat) [Morrisey et al. 1998]. In addition, the studies that found a post-training improvement in CMJ jump height report substantially different percentage improvements ranging from 5-21%. It would appear, based on the information provided in Table 2.30, that there are no obvious differences in training program design factors (duration, frequency, intensity) that may readily explain the inconsistent effects of squat training on CMJ jump height (Table 2.30). For example, Wilson et al. (1996) found a relatively small improvement in CMJ jump height of 1.9cm (5%) following a squat training program that incorporated a periodised design and heavy loads for three days a week over ten weeks. However, using an almost identical program design Wilson et al. (1993) found much larger improvements in CMJ jump height of 11.2cm (21%).

It could be suggested that differences in training background may explain why some individuals experienced greater post-training changes than others. That is, those with a longer training history would not be expected to experience as large a training effect as novices. However, novice weight lifters were utilised in the studies by Weiss et al. (1999) and Weiss et al. (2000), and neither found a post-training change in CMJ jump height.

Morissey et al. (1998) found a statistically significant increase in CMJ jump height in a group utilising a fast tempo squat but no statistically significant difference for those utilising a slow squat. While it may be tempting to suggest that individuals should thus utilise fast squats to facilitate greater jump height gains this may not be the case. The slow squat group actually had a larger mean jump height gain (20%) than the fast group (12%)! Perhaps the post-training change in the slow group was not statistically significant due to a large degree of inter-subject variation in training outcome. That is, some found the slow squat effective while others did not.

While it is impossible to explain with certainty why the squat was effective for some individuals but was not for others, it may be suggested that CMJ PDFs were stressed by the squat in the former instances but not in the latter. There are two potential explanations for such a phenomenon. Firstly, different individuals may experience different training stresses while carrying out the squat exercise (as suggested throughout sections 2.3.4.1 and 2.3.4.2), and secondly, different individuals may have different CMJ PDFs (as suggested throughout section 2.2). These respective hypotheses require more direct examination with research studies.

Table 2.30 The effect of squat training on CMJ jump height

Study	Subjects	Squat training	Load lifted	CMJ change	Statistical significance
Adams et al. (1992)	12 male Intermediate lifters	6 weeks, 2d.wk^{-1} 1-4 sets X 2-8 reps	50-100% 1RM	3.3cm	Yes
Morrisey et al. (1998)	21 women No lifting experience	7 wks, 3d.wk^{-1} 3 sets X 8 reps	80% 1RM	Fast group: 12% * Slow group: 20%**	Yes No
Weiss et al. (1999)	7 male Not currently lifting	7 wks, 3d.wk^{-1} 4 sets X 3-5 reps	87-93% 1RM	2.8 ± 4.1cm	No
Weiss et al. (2000)	6 male 6 female No lifting experience	8 wks, 3d.wk^{-1} 2-5 sets X 1-10 reps	75-100% 1RM	Parallel group: not provided ¥ Shallow group: not provided Ŧ	No
Wilson et al. (1996)	14 male Experienced, strength trained	8 wks, 2d.wk^{-1} 3-6sets X 6-10 reps	75-85% 1RM	11.2cm (21%)	Yes
Wilson et al. (1993)	15 male Recreational lifters	10 wks, 2d.wk^{-1} 3-6sets X 6-10 reps	75-85% 1RM	1.9cm (5%)	Yes

* Trained with a fast tempo squat (1 second down, 1 second up)
** Trained with a slow tempo squat (2 second down, 2 second up)
¥ Trained with a squat to parallel
Ŧ Trained with a shallow, quarter squat

2.3.5 The jump squat as a training exercise to improve countermovement jump ability

The jump squat exercise is undertaken with a weighted barbell, which rests on the back across the shoulders. The weight is lowered by flexion at the hip, knee and ankle before these same joints extend vigorously to propel the system (bar and body) upwards and ultimately off the ground (Figure 2.7). Loads utilised in the jump squat are typically lighter than those used in traditional squat training, for example, 30% 1RM loads are common (Lyttle et al. 1996; Wilson et al. 1993). Light loads and the ballistic nature of the movement mean that, unlike the squat, the jump squat is carried out at a speed closer to that of dynamic sporting movements like the CMJ. Another benefit of the jump squat over the squat is that the former does not require a deceleration of the barbell at the end of the concentric phase (Wilson et al. 1993).

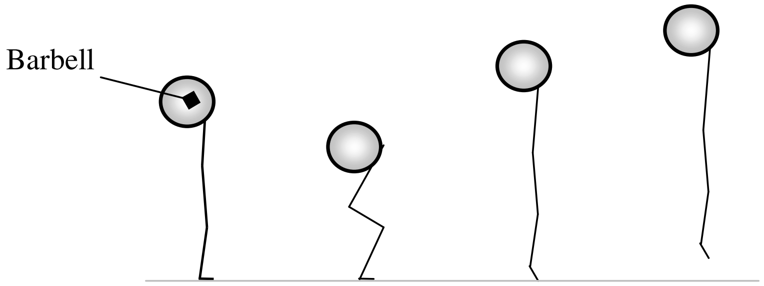

Figure 2.7 A graphical representation of the jump squat

The capacity to develop high levels of muscular power is seen as an important component of many sporting tasks, including the CMJ (Baker et al. 2001). Coaches therefore seek to prescribe training exercises that involve large power outputs in order to overload and thus enhance this neuromuscular capacity (Baker et al. 2001). In order for a training exercise to produce a large power output it must find a balance between force production and movement speed; power is the product of force and velocity, but force and velocity display an inverse relation in all muscular actions (Cormie et al. 2007b). Many authors believe that the jump squat, with an appropriate load, has the capacity to maximise lower extremity power production by optimising both force output and movement speed (Crewther et al. 2005).

When training to enhance lower extremity power production capacity, several authors suggest utilising a jump squat load that maximises neuromuscular power output (in the jump squat) [Crewther et al. 2005; Cormie et al. 2007c]. There is, however, much debate over what this optimal training load actually is. While numerous authors propose that 30% of 1RM is optimal (Alemany et al. 2005; Wilson et al. 1993), other loads ranging from 0-60% of 1RM have also been proposed (Cormie et al. 2007c). One potential reason for these conflicting findings is the varying subject populations that were tested. Baker et al. (2001) found that power trained athletes maximised power output in the jump squat at a higher relative load (40-60% 1RM) than individuals who were less experienced in specialised power training (30-45% 1RM). Cormie et al. (2007a) and Dugan et al. (2004) also contend that discrepancies between studies in the load that maximises power output in the jump squat is due to differences in the means by which data are collected and the methods of power calculation.

2.3.5.1 The acute training stress experienced by potential CMJ PDFs in the jump squat

Comparing the magnitudes of kinetic and kinematic parameters in the CMJ and the jump squat can give an indication of the acute training stress experienced by these parameters in the jump squat. Cormie et al. (2008) compared several parameter magnitudes across jump squat loads of 0kg (CMJ), 20kg, 40kg, 60kg and 80kg. Interestingly, peak whole body concentric power in each respective loading condition was not significantly greater than that in the CMJ (Table 2.31). In fact, peak powers produced using loads >40kg were significantly less than that produced in the CMJ. This finding suggests that, contrary to popular belief, loaded jump squats do not necessarily maximise lower body concentric peak power production. It would appear that for the subjects in this study body weight alone provided enough resistance to allow an optimal level of combined force production and velocity of movement. Bevan et al. (2010) also found that power output in a jump squat was maximal in unloaded as opposed to loaded conditions. Other studies that have shown that maximal power output in a jump squat is produced under loaded conditions ranging from 30-70 % 1RM (Baker et al. 2001;

Hoffman et al. 2005; Thomas et al. 2007) however none of these studies investigated power outputs in an unloaded jump squat condition.

Discrepancies in the extent to which peak power, or any parameter, is stressed in the jump squat over that in the CMJ may be expected due to inter-individual differences in neuromuscular capacity (Baker et al. 2001) or jump squat technique (Dugan et al. 2004). As already outlined, Baker et al. (2001) found that power trained athletes maximised power output in the jump squat at a higher relative load (40-60% 1RM) than individuals who were less experienced in specialised power training (30-45% 1RM). In addition Dugan et al. (2004) warns that different jump squat instructions may influence the neuromuscular output of the jump squat and thus the training stress it induces. For example, while some studies allow subjects to choose a self-selected COM amplitude (McBride et al. 2002) others employ more restrictive COM amplitudes (Stone et al. 2003).

Table 2.31 A comparison of jump squat parameter magnitudes across various loads (Cormie et al. 2008)

Parameter	External load				
	0kg (CMJ)	20kg	40kg	60kg	80kg
Whole body concentric peak power ($W.kg^{-1}$)	57.1	49.3	45.4 †	42.2 †	40.1 †
Whole body concentric peak force ($N.kg^{-1}$)	20.9	21.6	23.9 *	26.1 *	28.4 *
Whole body eccentric peak force ($N.kg^{-1}$)	18.9	19.5	21.5	22.3 *	24.5 *
COM amplitude (cm)	45	35 †	28 †	24 †	20 †
Whole body concentric RFD ($N.kg^{-1}.s^{-1}$)	24.9	28.8	27.9	25.1	22.9
Whole body concentric RPD ($W.kg^{-1}.s^{-1}$)	265.4	177 †	145.1 †	110.2 †	96.6 †

RFD – rate of force development; RPD – rate of power development

* Significantly greater than 0kg (CMJ)

† Significantly less than 0kg (CMJ)

Unsurprisingly, Cormie et al. (2008) found that as external loads in the jump squat increase, so to do peak whole body concentric and eccentric forces (Table 2.31). Jump squats with loads greater than 40kg produced significantly greater concentric forces than the CMJ, while jump squats with 60 and 80kg produced significantly greater eccentric peak forces. This study also found that the jump squat did not stress CMJ rate of force development or rate of power development (Table 2.31). Amplitude of the COM in the loaded jump squats was 40% less (on average) than that of the CMJ. However, the amplitude of the COM in the jump squat may be subject to inter-individual variation when subjects are allowed to produce a self-selected jump squat depth. Baker et al. (2001) for example, found that some subjects descended into a full squat position whereas Hori et al. (2009) reported a typical knee angle of 90º, akin to a parallel squat (half squat) position.

It would appear, as far as this author is aware, that no published research has quantified joint level kinetics and kinematics of the jump squat. Entering ‘jump squat’ into the Pubmed search engine (http://www.ncbi.nlm.nih.gov/pubmed/) on the 25th May 2010 resulted in 363 hits. Of these 363 journal articles none quantified joint level kinetics and kinematics of the jump squat. It is not possible therefore to gain an insight into the potential training effect that the jump squat may have on joint level parameters.

2.3.5.2 The effect of jump squat training on potential CMJ PDFs

Both Newton et al. (1999) and Hori et al. (2008) found significant increases in CMJ concentric peak power of 8.0 ± 8.9% and 5.1% respectively, following jump squat training interventions. While these findings highlight that jump squat training can enhance CMJ concentric peak power at a group level the large standard deviation reported by Newton et al. (1999) suggests that some individuals within that training group may not have experienced a significant improvement. It would appear therefore that the jump squat might not have stressed every individual’s neuromuscular power production capacity. In addition, Newton et al. (1999) found no significant post training changes in CMJ peak force or rate of force development following jump squat training. As far as this author is aware no other studies have investigated changes in CMJ parameters following a period of jump squat training.

2.3.5.3 The effect of jump squat training on countermovement jump ability

The details of five training studies that examined the effect of jump squat training on CMJ jump height are presented in Table 2.32. While two of the studies presented found significant improvements in jump height (Wilson et al. 1993; Lyttle et al. 1996), another two found no significant change (Blazevich et al. 2003; Hoffman et al. 2005). In the remaining study, Newton et al. (1999) found a significant but small post-training enhancement (5.9%) in a jump and reach task, but no change in jump height in a CMJ without an arm swing. Of note, while Wilson et al. (1993) and Lyttle et al. (1996) both found a post-training increase in CMJ jump height, the percentage improvement found by Wilson et al. (1993) was much larger (17.6% versus 7.9%). Additionally, Lyttle et al. (1996) found a notably large standard deviation in their training group's percentage improvement (± 6.5%). This suggests that some individuals within the training group may not have increased their CMJ jump height following jump squat training.

Several program design variables may partly explain why some of the studies reported in Table 2.32 did not result in significant improvements in CMJ jump height. A training duration of five weeks as employed by Blazevich et al. (2003) and Hoffman et al. (2005) may not have been long enough to facilitate enhancements in neuromuscular capacity. Also, the studies that found no post-training improvement in CMJ jump height all used relatively heavy jump squat loads, which may not have induced an optimal training stress. Loads of 0-60% of 1RM have been identified as optimal for jump squat training (Cormie et al. 2007c) but the ineffective training studies presented in Table 2.32 regularly prescribed heavier loads. Perhaps the particularly heavy loads prescribed by Blazevich et al. (2003) induced an over-training effect, which may explain the group trend towards a reduction in jump height following training.

Table 2.32 The effect of jump squat training on CMJ jump height

Study	Subjects	Jump squat Training	Load lifted	CMJ change	Statistical significance
Blazevich et al. (2003)	15 male 8 women Various sports No previous JS experience	5 weeks, 2d.wk^{-1} 3 sets X 6 reps	Day 1: 85-90% 1RM Day 2: 44-73% 1RM	-4cm (-8.9%)	No
Hoffman et al. (2005)	15 male American football Resistance trained	5 weeks, 2d.wk^{-1} 4 sets X 4 reps	70% 1 RM	2.3cm (3.7%)	No
Newton et al. (1999)	8 male Volleyball Resistance trained	8 weeks, 2d.wk^{-1} 6 sets X 6 reps	2 sets @ 30% 1RM 2 sets @ 60% 1RM 2 sets @ 80% 1RM	CMJ A*: no change CMJ B*: 5.9 ± 3.1%	CMJ A: No CMJ B: Yes
Lyttle et al. (1996)	11 male Various sports Not resistance trained	8 weeks, 2d.wk^{-1} 2-6 sets X 8 reps	30% 1RM	7.9 ± 6.5%	Yes
Wilson et al. (1993)	16 male Recreational lifters	10 weeks, 2d.wk^{-1} 3-6 sets X 6-10 reps	30% 1RM	6cm (17.6 ± 10.7%)	Yes

* CMJ A = jump and reach; CMJ B = CMJ on force plate, arms restricted
JS = jump squat

While differences in program design variables may partly explain why the jump squat was ineffective in some of the studies outlined in Table 2.32, they cannot explain the large discrepancy in percentage improvement found by Wilson et al. (1993) and Lyttle et al. (1996). Both of these studies were of a similar duration and utilised a similar training volume and intensity (Table 2.32). In spite of this, Wilson et al. (1993) found almost twice as large an improvement in CMJ jump height [17.6%] compared to Lyttle et al. (1996) [7.9%]. Moreover, program design factors cannot explain the inconsistent training outcomes of individuals in the study of Lyttle et al. (1996). All individuals were of a similar training background and carried out the same training program at the same relative intensity, yet some individuals did not improve their CMJ jump height while others did. In light of the inconsistent outcomes of the three studies discussed here it could be suggested that the jump squat may be effective at stressing and enhancing some individual's CMJ PDFs but is less effective, or is not effective, at doing so for others. One potential reason for this phenomenon is that the training stress imposed by the jump squat may vary from individual to individual (as has been suggested above in sections 2.3.5.1 and 2.3.5.2). In addition section 2.2 provided evidence to suggest that different individuals have the potential to possess different CMJ PDFs. This may also, at least in part, explain why the jump squat may be effective at enhancing some individual's CMJ jump height but is not as effective at doing so for other individuals. These respective hypotheses clearly require more direct examination.

2.3.6 The power clean as a training exercise to improve countermovement jump ability

The power clean, a derivative of the clean and jerk weightlifting exercise, is becoming increasingly popular as a means of enhancing dynamic performances (Kawamori and Haff 2004) like the CMJ. At the commencement of the power clean the barbell rests on the floor while the lifter assumes a body position similar to that taken at the start of a deadlift (Figure 2.8). The lift commences with a forceful extension of the hips and knees, while the arms, acting like rigid cables attached to the bar, remain fully extended (Earle and Baechle 2000). This phase of the power clean is known as the first pull. The first pull is followed by a transition phase where the knees re-flex under the bar as it rises above them (Earle and Baechle 2000). The transition phase is said to place the body in position that will optimise power production in the next phase of the lift, the second pull (Souza et al. 2002). The second pull involves an explosive extension of the hip, knee and ankle joints where the lifter pushes against the ground as hard and as fast as possible (Hori et al. 2005). This high power phase of the power clean closely resembles the thrust phase of the CMJ (Garhammer 1993). As the bar reaches near maximal height the arms are rotated around and under the bar to catch it on the anterior aspect of the shoulder while cushioning the impact with a quarter front squat (Earle and Baechle 2000).

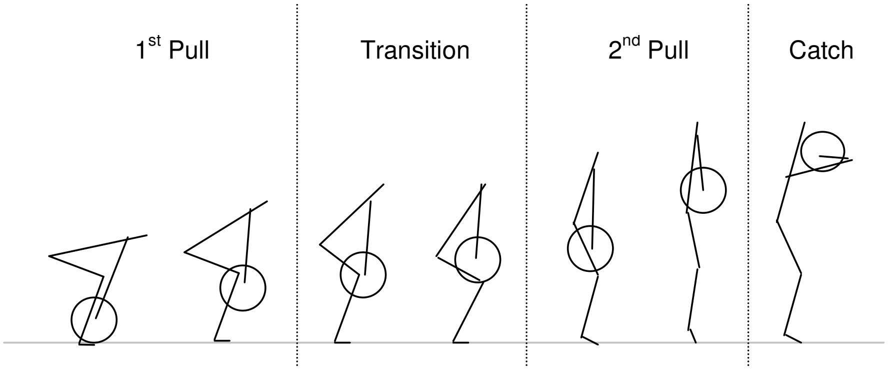

Figure 2.8 A graphical representation of the power clean

The power clean is typically carried out with relatively heavy loads of approximately 80% 1RM (Cormie et al. 2007c; Kawamori and Haff 2004). Kawamori and Haff (2004) suggest that the use of such heavy loads in combination with the high movement velocity of the exercise means that the power clean may facilitate a large whole body power output. In addition, the power clean does not involve a large deceleration of the barbell at the end of the concentric phase, an aspect of traditional resistance training that is often criticised (Wilson et al. 1993)

2.3.6.1 The acute training stress experienced by potential CMJ PDFs in the power clean

Comparing the magnitudes of kinetic and kinematic parameters in the CMJ and the power clean may give an indication of the acute training stress experienced by these parameters in the power clean. It would follow that such an analysis might give an indication of the ability of the power clean to enhance these CMJ parameters. Kawamori et al. (2005) detailed whole body peak force, power and rate of force development values for the CMJ and hang power cleans at different intensities (Table 2.33). The hang power clean mimics the second pull phase of the full power clean; the phase where maximal forces, velocities and powers are produced (Kawamori et al. 2006). From the values provided in Table 2.33 it is clear that whole body concentric peak power is not stressed in the power clean in comparison to the CMJ at any of the percentage 1RMs detailed. It should be noted however that power output in a full power clean would be expected to be greater than that of a hang power clean due to SSC utilisation in the former. Kawamori et al. (2005) also found that both whole body concentric peak force and rate of force development were acutely stressed in the hang power clean at each respective percentage of 1RM.

Table 2.33 A comparison of whole body concentric kinetics in the CMJ and in hang power cleans of various intensity (Kawamori et al. 2005)

	CMJ	70% 1RM	80% 1RM	90% 1RM
Whole body concentric peak power ($W.kg^{-1}$)	60.9 ± 8.2	45.6 ± 5.2	45.2 ± 6.4	43.8 ± 5.2
Whole body concentric peak force ($N.kg^{-1}$)	25.7 ± 2.3	37.3 ± 3.6	37.9 ± 3.6	38.5 ± 3.6
Whole body concentric RFD ($N.kg^{-1}.s^{-1}$)	157.8 ± 75.6	215.7 ± 77.2	225.3 ± 80.0	231.6 ± 85.5

Enoka (1988) calculated peak concentric power outputs about the hip, knee and ankle during a power clean (86% 1RM) carried out by both skilled and less skilled weightlifters (Table 2.34). The author noted that the knee and ankle underwent two phases of extension, first and second pull, separated by a phase of flexion (transition phase) while the hip extended throughout the movement. As evident from the values provided in Table 2.34, concentric power outputs at each joint were larger in the second pull than in the first pull. In addition, peak concentric power outputs generated at the hip were much larger than those generated at the knee or ankle. This study did not directly compare joint power outputs in a power clean with those of a CMJ. However, by comparing data provided below in Table 2.34 with that provided previously in Table 2.3 a comparison is possible. Peak power outputs for the power clean reported in the current study for the skilled lifters (hip: 11.9W.kg^{-1}, knee: 2.4W.kg^{-1}, ankle: 3.9W.kg^{-1}) are much lower than those typically reported for the CMJ (hip: 12.6-19.5W.kg^{-1}, knee: 15.6-30.1W.kg^{-1},ankle: 17.1-28.8 W.kg^{-1}). While this suggests that joint peak concentric power output is not stressed in the power clean in comparison to the CMJ it is worth noting that between study differences in power output magnitudes may arise due to variations in the means by which data is collected and the methods of power calculation used (Cormie et al. 2007a)

Table 2.34 Joint concentric peak power during a power clean (86% 1RM) carried out by skilled and less-skilled weightlifters (Enoka 1988)

		Skilled weightlifters	Less skilled weightlifters
Hip peak power (W.kg^{-1})	First pull	8.7 ± 1.4	7.1 ± 1.5
	Second pull	11.9 ± 4.1†	7.1 ± 3.9
Knee peak power (W.kg^{-1})	First pull	2.1 ± 0.8	2.6 ± 1.1
	Transition*	-2.5 ± 1.5	-1.3 ± 0.8
	Second pull	2.4 ± 3.7	3.2 ± 2.1
Ankle peak power (W.kg^{-1})	First pull	2.1 ± 0.4	1.8 ± 1.6
	Transition*	-0.9 ± 0.9	-1.3 ± 0.6
	Second pull	3.9 ± 1.8	3.2 ± 1.6

* Peak power developed in an eccentric contraction

† Significantly different compared to less skilled

Enoka (1988) also found that more skilled weightlifters produced a significantly greater hip concentric peak power output during the second pull than less skilled weightlifters (Table 2.34). This highlights the fact that the power clean is a very technical exercise and that even within the weightlifting community inter-individual differences exist in how individuals produce the lift. Another study that highlights the importance of power clean technique is that of Winchester et al. (2005) who examined the effect of power clean technique training in subjects with one years power clean experience. The authors found that four weeks of technique training using both visual and verbal cues resulted in significant increases in the amount of whole body peak power and force produced in the power clean. In a power clean at 90% 1RM for example, peak force increased significantly by 13.5% while peak power increased by 7.2%. Both the studies of Winchester et al. (2005) and Enoka (1998) highlight the potential for individuals at different stages of power clean technique development to produce power cleans with notably different neuromuscular outputs. In addition, Garhammer (1993) suggests that variations between athletes in how they produce a given lift are also likely to arise due to differences in body segment lengths. In light of all of this, inter-individual differences in the training stress imposed by the power clean may well exist. However, no previous studies have specifically examined this hypothesis.

As far as this author is concerned there is a lack of information in the published literature regarding whole body and joint level power clean kinematics. Entering 'power clean' into the pubmed search engine (http://www.ncbi.nlm.nih.gov/pubmed/) on the 23rd of May 2010 resulted in 562 hits. Of these 562 journal articles 32 pertained to the power clean weightlifting exercise. Of these 32 articles none provided kinematic variables such as hip, knee and ankle angles or COM amplitudes produced during the power clean. It is not possible therefore to speculate as to the potential training effect that the power clean may have on CMJ kinematics.

2.3.6.2 The effect of power clean training on potential CMJ PDFs

It would appear that only two studies have examined the effect of power clean training on a potential CMJ PDF, in this case whole body concentric peak power. Hoffman et al. (2004) found no change in whole body concentric peak power following a period of weightlifting training that included power cleans. This supports the suggestion outlined in the previous section that peak power is not appropriately stressed in the power clean relative to the CMJ. In contrast to these findings Howard (1997) found a significant increase in CMJ peak power output (an increase of $2658 J.s^{-1}$) following eight weeks of power clean training. The participants used in Howard's study however had far less training experience than those utilised by Hoffman et al. (2004). Due to the untrained nature of the participants used by Howard (1997) improvements in CMJ peak power may have been possible following the addition of any form of resistance training. Indeed, another training group in the same study significantly improved CMJ peak power (increase of 2598J.s^{-1}) following eight weeks of traditional heavy load squatting (Howard 1997).

2.3.6.3 The effect of power clean training on countermovement jump ability

While the use of weightlifting exercises like the power clean are becoming increasingly popular (Tricoli et al. 2005) there are only a few studies that have examined their effects on CMJ jump height. Three such studies are outlined in Table 2.35. Howard (1997) found a significant improvement of 9cm following eight weeks of power clean training, while Channell and Barfield (2008) and Tricoli et al. (2005) found more modest post-training increases of 2.6 and 2.8cm, respectively (Table 2.35). The large difference in post-training enhancement in the study by Howard (1997) is likely due to the fact that the participants used in that study had less resistance training experience than the subjects used in the other two studies.

Interestingly, despite the large group improvement in jump height of 9cm, Howard (1997) found that two individuals actually decreased their CMJ jump height following power clean training. In addition, the large standard deviation in the group mean improvement reported by Channell and Barfield (2008) [2.6 ± 4.7cm] also indicates that some subjects within the training group did not experience a significant post-training increase in jump height. Collectively these findings indicate that while the power clean may be effective at enhancing some individual's CMJ jump height, it may not be as effective at doing so for other individuals. One potential reason for this phenomenon is that the training stress imposed by the power clean may vary from individual to individual (as has been suggested above in sections 2.3.6.1 and 2.3.6.2). In addition section 2.2 provided evidence to suggest that different individuals have the potential to possess different CMJ PDFs. This may also (in part) explain why the power clean may be effective at enhancing some individual's CMJ jump height but is not as effective at doing so for other individuals. These respective hypotheses clearly require more direct examination.

Table 2.35 The effect of power clean training on CMJ jump height

Study	Subjects	Power clean training	Load lifted	CMJ change	Statistical significance
Howard (1997)	13 male 8 female No weight training experience	8 weeks, 2d.wk^{-1} 3 sets X 8-12 reps	Not provided	9cm	Yes
Channell and Barfield (2008)	11 male American football Limited weight training	8 weeks, 3d.wk^{-1} 3-5 sets X 5-10 reps *	60-75% 1RM	2.6 ± 4.7 (4.5%)	Yes
Tricoli et al. (2005)	12 male Recreationally weight trained	8 weeks, 3d.wk^{-1} 4 sets X 4 reps **	90% 1RM	2.8cm (6.6%)	Yes

* Training also included push-jerk, lunges and leg press

** Training also included a high pull, clean and jerk and half-squat

2.3.7 Implications arising from the outcomes of training studies aimed at improving countermovement jump ability

The results of several training studies that have examined the effects of drop jump training, squat training, jump squat training and power clean training, on CMJ jump height have been presented above (sections 2.3.3-2.3.6). In general, the findings of these studies as to the effectiveness of each respective exercise at enhancing jump height are inconsistent (see Tables 2.24, 2.30, 2.32, 2.35). These inconsistencies are typically manifest in three ways. Firstly, there are often conflicting findings regarding whether training with a given exercise can actually improve CMJ jump height or not. Secondly, even when several studies find an exercise has significantly improved CMJ jump height the magnitude of enhancement can vary quite dramatically across studies. Thirdly, on several occasions where an exercise has been found to increase a group's mean jump height there is evidence to suggest that a number of individuals within the group did not experience an enhancement. There is also no compelling evidence to suggest that between study differences in subject characteristics, training intensity, frequency or volume can fully explain these inconsistent training outcomes (see Tables 2.24, 2.30, 2.32, 2.35). The resounding implication of these findings is that coaches cannot be sure as to which training exercise will be most effective at enhancing their athletes' CMJ jump height. Obviously this is not a satisfactory situation, especially when working with elite athletes or in situations where time constraints limit the use of just one training exercise to improve CMJ ability. There is a need therefore for the development of a biomechanical diagnostic and prescriptive pathway that may facilitate the pre-training identification of the most suitable training exercise to enhance athletes' jumping ability.

It has also become apparent, from the review to this point, that different individuals may both possess different CMJ PDFs (section 2.2) and experience different training stress in the same training exercise (sections 2.3.3-2.3.6). While Bates (1996) would suggest that such inter-individual differences are bound to exist due to the uniqueness of individuals, no research study has specifically examined this hypothesis. Nevertheless it appears logical for any proposed biomechanical pathway to consider that (a) different individuals (and thus groups) may have different CMJ PDFs, and (b) different individuals (and thus groups) may experience a different training stress in the same training exercise. Such considerations are important, as it is likely that these inter-individual differences may, at least in part, explain why training outcomes are so inconsistent in the first place.

2.4 A biomechanical diagnostic and prescriptive pathway to assist training exercise selection

The previous section highlighted the need for the development of a means to identify, prior to training, the most suitable training exercise to enhance an athlete's jumping ability. To this end a biomechanical diagnostic and prescriptive pathway is proposed (Figure 2.9). The diagnostic aspect of the pathway (steps one and two) requires a biomechanical analysis of the CMJ and each training exercise under examination. This allows the identification of CMJ performance related factors (PRFs)[1] and the training stress these CMJ PRFs experience in each training exercise. It is hoped that this information will provide an insight into the probable enhancements that CMJ PRFs will experience following training with each exercise (step three). Post-training enhancements in CMJ PRFs are assumed to lead to improvements in CMJ jump height. In light of this, the exercise that is deemed most likely to induce the greatest enhancements in CMJ PRFs would be considered the most appropriate exercise to employ to enhance jump height (step four). Once the most appropriate training exercise to enhance CMJ jump height is selected all that remains is to prescribe an appropriate training regimen. A more detailed description of the proposed pathway is provided below where it will also become apparent that the pathway can be applied to a particular group, subgroup or individual.

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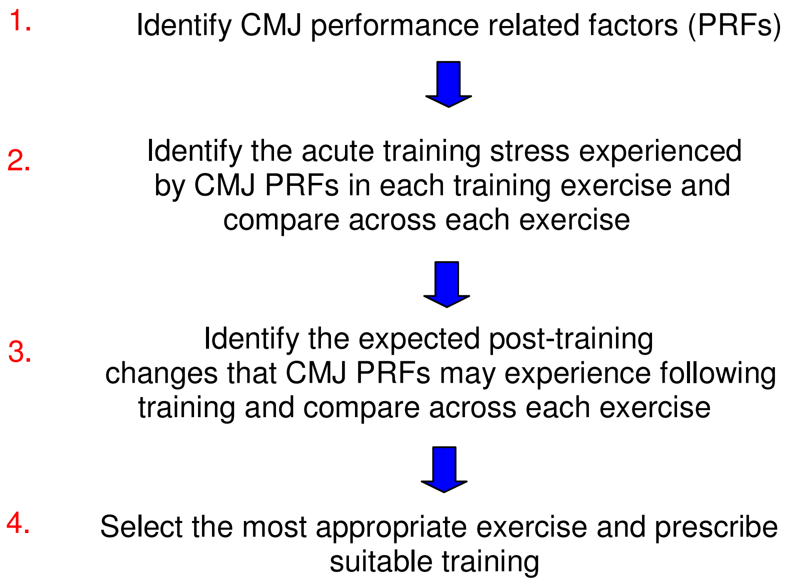
[1] While CMJ PDFs are those CMJ parameters that ultimately determine jump height they cannot be identified experimentally in an acute testing session, as a true cause and effect relationship cannot be established. Instead, CMJ PRFs are identified on the assumption that they are likely to be CMJ PDFs. CMJ PRFs are those CMJ parameters that are significantly correlated with CMJ jump height (see section 2.2.2 for more details).



1. Identify CMJ performance related factors (PRFs)
2. Identify the acute training stress experienced by CMJ PRFs in each training exercise and compare across each exercise
3. Identify the expected post-training changes that CMJ PRFs may experience following training and compare across each exercise
4. Select the most appropriate exercise and prescribe suitable training

Figure 2.9 A proposed pre-training biomechanical diagnostic and prescriptive pathway

As outlined in Figure 2.9 step one of the proposed pathway involves identifying all relevant CMJ PRFs. Researchers typically identify CMJ PRFs through the use of multiple bivariate correlations (Dowling and Vamos 1993; Harman et al. 1990; Jaric et al. 1989). A bivariate correlation measures the extent to which variance in CMJ jump height can be explained by variance in a given CMJ parameter (e.g. peak power). Another means by which some researchers have identified CMJ PRFs is through multiple regression analysis. It is the view of this author however, that multiple bivariate correlations are better suited to the current application than a multiple regression analysis (see section 2.4.1 below).

Previous studies that have used multiple bivariate correlations to identify CMJ PRFs have done so using group based statistical analysis (Dowling and Vamos 1993; Harman et al. 1990; Jaric et al. 1989). That is, measuring the extent to which inter-subject variability in CMJ jump height can be explained by inter-subject variability in each CMJ parameter under investigation. However, as highlighted throughout section 2.2, there is evidence to suggest that different individuals may have different CMJ PRFs (Vanezis and Lees 2005; Aragon-

Vargas and Gross 1997a). In light of this, CMJ PRFs identified using a group-based analysis may not be an accurate reflection of every individual's CMJ PRFs (Bates et al 2004; Dufek et al. 1995). This is because inter-individual differences in CMJ PRFs may be averaged out, or masked, in group-based analyses (Bates et al 2004; Dufek et al. 1995) [as previously outlined in section 2.2.3]. It is apparent therefore that in order to identify the most effective training exercise for each individual athlete, it may be necessary to identify each individual's CMJ PRFs. One method of identifying an individual's CMJ PRFs is through the use of a single-subject analysis (Dufek et al. 1995). A single subject analysis involves statistically analysing repeat performances from one individual. That is, measuring the extent to which intra-subject variability in CMJ jump height (across several CMJ repetitions) can be explained by intra-subject variability in each CMJ parameter under investigation.

Step two of the proposed pathway (Figure 2.9) involves identifying the acute training stress experienced by the CMJ PRFs in each training exercise of interest. It is theorised that such an analysis will allow a pre-training insight into the likely post-training change that CMJ PRFs will experience following training with each respective exercise. This step in the pathway is based on the theory of training overload which states that in order for a given CMJ PRF to be enhanced with training it must be stressed at a level beyond which it is accustomed (Zatsiorsky and Kraemer 2006). Bobbert (1990) suggests that an acute training stress is present when a given training exercise produces a higher mechanical output than that produced in the CMJ. Training stress may therefore be identifiable statistically using tests of significant difference. This convention could also be extended to jump parameters that are not purely mechanical in nature. That is, a training exercise may also acutely stress CMJ technique and coordination parameters (see section 2.3.1).

Previous studies that have statistically evaluated the acute training stress experienced by CMJ parameters in a training exercise have done so using group based statistical analysis (Bobbert et al. 1986a; Bobbert et al. 1987a; Bobbert et al.

1987b; Holcomb et al. 1996a). However, as highlighted throughout section 2.3, there is evidence to suggest that different individuals may experience different training stresses when carrying out a given exercise (Bobbert et al. 1986; Enoka 1988). Thus the training stress experienced by a group, as identified using a group-based analysis, may not be an accurate reflection of the training stress experienced by every individual (Bates et al 2004; Dufek et al. 1995). It is apparent therefore that in order to identify the most effective training exercise for every athlete, it may be necessary to identify the training stress that every athlete experiences. This can be facilitated with the use of a single subject analysis.

The third step of the proposed pathway (Figure 2.9) involves using the information gathered in step two to identify the likely post-training magnitude changes that CMJ PRFs will experience following training in each exercise. That is, an appropriate training stress is likely to lead to a post-training CMJ PRF enhancement while no stress is likely to lead to no post-training change (Bobbert et al. 1986a). In addition, a training exercise inducing a greater training stress than another may be expected to induce a greater training effect (Bobbert et al. 1987a). By comparing the likely post-training CMJ PRF magnitude changes that each training exercise will induce, it is possible to select an exercise that appears to be best suited to enhancing CMJ PRFs, and in turn CMJ jump height. Once the most appropriate training exercise is selected it is simply a matter of prescribing a suitable training regime in terms of training duration, frequency, volume and intensity (step 4).

While potential limitations in applying the proposed pathway (Figure 2.9) using a group level analysis may be prevented with the use of a single-subject analysis (as outlined above) there are, in turn, some potential limitations in applying the pathway with a single-subject analysis (see section 2.4.2 below). It may therefore be worth applying the pathway using a combination of both a group and subgroup [cluster] analysis. Firstly, a group analysis could be applied as normal, that is, to identify the exercise most likely to improve the group's mean CMJ jump height. Secondly, a cluster analysis could then identify subgroups of individuals who are unlikely to derive a notable improvement from this training exercise. Those identified as unlikely to benefit from the selected exercise could be combined to form a new group and the group analysis re-run to find a more appropriate training exercise.

A cluster analysis establishes homogenous groups of individuals based on scores across a number of variables (Park et al. 2005). In this case, the variables of interest are the group level CMJ PRFs, while the scores are the magnitudes of CMJ PRF training stress each individual experiences in the training exercise (that is, parameter magnitude in CMJ - parameter magnitude in training exercise). This analysis assumes that while each individual has the capacity to experience a unique training stress in a given training exercise, some individuals may experience a more similar training stress than others. The combined use of a group and subgroup analysis may allow the identification of the most appropriate training exercise for different subgroups within the main group, and as such, is a middle ground between the extremes of a group analysis and a single-subject analysis.

2.4.1 Multiple stepwise regression and factor analysis; alternative methods of CMJ performance related factor identification that were considered

The first step in the proposed pathway (Figure 2.9) involves identifying all relevant CMJ PRFs. As outlined above this can be achieved through the use of multiple bivariate correlations. However, an alternative method of CMJ PRF identification exists called multiple stepwise regression. This form of analysis establishes the combined influence that biomechanical parameters exert over CMJ jump height; something multiple bi-variate correlations cannot do. Multiple stepwise regression works by fitting various combinations of parameters (predictors) into models that are each tested for their ability to predict performance outcome (jump height). Perhaps the most common methods of stepwise regression are forward and backward regression (Field 2005). The backward method starts out with a model containing all predictors and then removes those that are deemed dispensable while the forward method starts out with a model that contains the best single predictor and then adds predictors that significantly enhance predictive ability (Field 2005). Both methods allow the identification of a best predictor model, that is, the set of CMJ parameters that best predicts CMJ jump height (Aragon-Vargas and Gross 1997b). This set of parameters could therefore be considered to be those CMJ PRFs required for step one in the proposed pathway (Figure 2.9). However, as will be outlined below, the inter-related nature of numerous CMJ parameters precludes the use of multiple stepwise regression at identifying CMJ PRFs in the proposed pathway.

While the set of CMJ parameters identified using a multiple regression may be the best possible at predicting jump height, they are selected in a purely pragmatic fashion and may not contain all relevant CMJ PRFs. A major problem with multiple regression exists when several predictor variables are correlated with each other, referred to as multicollinearity (Field 2005). When multicollinearity is present a situation may arise where one of two inter-related variables is excluded from a predictor model because its addition does not significantly increase the predictive ability of the model (Field 2005). Such a problem is likely to arise in CMJ analysis as numerous CMJ parameters are inter-related. There is a risk therefore of excluding relevant CMJ parameters when identifying CMJ PRFs using multiple stepwise regression. An example of this phenomenon can be found in the literature. Aragon-Vargas and Gross (1997a) found that amplitude of movement was the best single predictor of jump height for individual A (r = 0.56) but was not included with other CMJ parameters in the best three multiple regression predictor models of CMJ jump height.

Another problem with stepwise regression can occur when two variables that are highly negatively correlated with each other are included in the same regression model. This may result in the coefficient of one variable changing sign to accommodate the other variable in the model (Hair et al. 1987). Such a phenomenon occurred in the group level analysis of CMJ PRFs carried out by Aragon-Vargas and Gross (1997b). Peak hip moment was by itself positively correlated with CMJ jump height (r = 0.53) but when included with other variables in a regression model (model 16, pg36) it displayed a negative relationship. Identifying CMJ PRFs using multiple regression techniques may therefore provide misleading information regarding the relationship that a CMJ PRF has with jump height.

A factor analysis is another form of statistical analysis that may be used to identify CMJ PRFs. This form of analysis groups several observed variables into a smaller number of unobserved variables called factors (Field 2001). Interpreting the results of a factor analysis can however be difficult (Field 2001). Firstly, a given factor may be created where some of the variables contained in that factor have no obvious inter-relationship. Secondly, there is no standard objective procedure regarding the number of factors that should be created. Finally, there is a danger of losing meaningful information by reducing the number of variables of interest.

In light of the problems regarding both multiple stepwise regression and factor analysis discussed above it was considered more appropriate to utilise bi-variate correlations to identify CMJ PRFs in the current study.

2.4.2 Potential limitations in applying the proposed biomechanical diagnostic and prescriptive pathway using a single-subject analysis

Identifying an individual's CMJ PRFs using a single-subject analysis relies on the presence of intra-subject variability in each respective CMJ parameter under investigation, and in CMJ jump height itself. Intra-subject variability can be defined as variability within an individual's repetitions of a given task (Aragon-Vargas and Gross 1997a). Many authors feel that intra-subject variability is inherent in all motor tasks, such as the CMJ, due to the complex systems and constraints that must interact in order to produce movement (Bates 1996; James 2004; Latash et al. 2002; Stergiou and Scott 2005). Thus, as the system has multiple degrees of freedom, several attempts at the same task will lead to different performance kinetics, kinematics, patterns of muscle activity (Latash et al. 2002) and performance outcomes. As an individual becomes more familiar with the task in question the levels of intra-subject variability may be reduced, however, even in the most simple and seemingly automated performances some variability still persists (Muller and Sternad 2009).

Intra-subject variability has been discussed primarily from two theoretical perspectives, motor control theory and dynamical systems theory (Bates 1996). Motor control theory views variability as random error in movement planning, execution and outcome (Bates 1996; James 2004; Stergiou et al. 2004). From this perspective variability is seen as both detrimental to the performance of a task (James 2004) and as a nuisance that necessitates the collection of several trials from a subject in order to obtain representative data. More recently a dynamical systems theory of variability has emerged (James 2004; Stergiou et al. 2004) which suggests that variability may have a deterministic origin (James 2004), that is, intra-subject variation may have a functional relevance.

Those who ascribe to the dynamical systems theory of variability have suggested different reasons as to why intra-subject variability exists. It has been postulated that variability may facilitate the exploration of more optimal neuromuscular solutions for the performance of a given task (James 2004). This notion supports the method of examining intra-subject variability as a means of identifying an individual's CMJ PRFs (Figure 2.9, step one). However, other functions of intra-subject variability have been proposed that may actually reduce the validity of using a single-subject analysis to identify relevant CMJ PRFs. For example, James (2004) suggests that intra-subject variability in the performance of a given task may exist in order to reduce the risk of overuse injury by distributing stresses among different tissues (James 2004) or indeed different joints. In addition, Latash et al. (2007) suggests that an individual's neuromuscular system may allow a high level of co-variance in elemental variables in order to stabilise more important performance variables (Latash et al. 2007). Support for this theory is provided by Winter (1984) who examined joint kinetic and kinematic moment patterns in human gait. The author found large intra-subject variability in hip and knee moment patterns during gait despite the fact that whole body kinetic patterns, and joint and whole body kinematic patterns, were quite consistent. It would appear therefore that the function of intra-subject variability may not solely be to explore more optimal neuromuscular solutions for a given task. In light of this, and the fact that in some cases intra-individual variability may simply be due to random movement error, there is an increased risk of finding chance correlations between certain CMJ parameters and jump height. Thus when attempting to identify an individual's CMJ PRFs using a single subject analysis there is a risk of identifying CMJ parameters as CMJ PRFs when they actually are not. Moreover, the notion that the neuromuscular system attempts to minimise variability in parameters closely related to a task's performance, or indeed in performance outcome itself (Latash et al. 2007), has serious implications. Such a situation may increase the risk of not being able to identify a CMJ parameter as a CMJ PRF when it actually is. Indeed Aragon-Vargas and Gross (1997a) acknowledged that a lack of sufficient intra-subject variability in both CMJ jump height and CMJ parameters is a major concern when attempting to identify CMJ PRFs using single-subject analysis.

2.4.3 'Strength diagnosis', another exercise prescription method that has been proposed to assist training exercise selection

Newton and Dugan (2002) have proposed a method of training exercise selection called a 'strength diagnosis' that is quite different to the proposed pathway outlined above (Figure 2.9). The strength diagnosis method is based on the notion that certain strength measures represent independent qualities of the neuromuscular system and that these qualities can be assessed and trained separately (Newton and Dugan 2002). The first step of the strength diagnosis is to determine the strength qualities of the target activity. The authors propose six strength qualities: maximum strength, high load speed strength, low load speed strength, rate of force development, reactive strength and skill performance (coordination). Once the strength qualities of the task have been identified, through a biomechanical evaluation of the task and an analysis of high-level performers, athletes are tested on these strength qualities. For example, maximum strength is tested using a 1RM strength test while low load speed strength is tested using low load ballistic exercises (Newton and Dugan 2002). Following testing, strength deficiencies can be determined and training exercises prescribed to address these deficiencies. This latter prescriptive step is based on the assumption that each of the different strength qualities outlined are best trained with certain training exercises. For example, traditional heavy resistance training would be optimal at enhancing maximal strength while low load ballistic exercises would be most suited to improving low load speed strength (Newton and Dugan 2002). One advantage of the strength diagnosis over the proposed biomechanical diagnostic and prescriptive pathway is that it involves direct testing of various neuromuscular capacities for weakness. As such it appears the better method to identify general aspects of neuromuscular capacity that are limiting performance outcome. The proposed diagnostic and prescriptive pathway associated with the present thesis on the other hand has the following advantages over the strength diagnosis:

(a) The proposed pathway identifies potential PDFs through an analysis of the task of interest and is therefore extremely task specific. In contrast, the strength diagnosis method involves less task specific tests and as a result training is tailored more toward enhancing a certain strength quality rather than the performance outcome of interest.

(b) The proposed pathway can identify likely whole body and joint level PDFs. In contrast, the strength diagnosis tests are all tests of whole body capacity. While some of the proposed strength tests could be adapted to test joint capacity the validity of such tests could be questioned due to a lack of task specificity.

(c) The proposed pathway prescribes a training exercise based on an analysis of potential PDFs and the acute training stress these potential PDFs experience in various training exercises. The strength diagnosis on the other hand assumes that one type of training exercise is best suited to training a particular PDF across all individuals. For example, low load speed strength is best trained in all individuals using low load ballistic exercises. Such an assumption is not necessarily accurate; evidence that different individuals have the capacity to experience different training stresses in a given training exercise is provided throughout section 2.3.

Based on a, b and c above it appears that the proposed biomechanical diagnostic and prescriptive pathway (Figure 2.9) has the potential to be the better method of identifying task specific aspects of a performance that are limiting performance outcome. In addition, the proposed pathway ultimately employs a more reasoned method of training exercise selection. Perhaps, however, it is wrong to pit both methods of training exercise selection against each other. It could in fact be suggested that both methods may have their own place in an athlete's training season. The strength diagnosis would appear well suited to exercise selection in the pre-season phase of training where general training is employed that is not necessarily task specific. The diagnostic and prescriptive pathway on the other hand may be better suited to exercise selection closer to, or within, the in-season phase of an athlete's training. Here a more careful method of exercise selection is required and exercises need to be focused entirely on enhancing the performance outcome of interest. It should be noted that the current study aims to investigate the efficacy of the proposed biomechanical diagnostic and prescriptive pathway (Figure 2.9) alone and not the combined use of a strength diagnosis and diagnostic and prescriptive pathway.

2.5 Conclusion

This review examined numerous potential CMJ PDFs. In so doing, evidence was provided to suggest that different individuals have the capacity to possess different CMJ PDFs. The ability of respective training exercises (drop jump, squat, jump squat and power clean) to stress potential CMJ PDFs and enhance CMJ jump height was then examined. Based on this review it is apparent that different individuals may have the capacity to experience different training stresses in a given exercise. Results of previous training studies that have examined the effectiveness of the drop jump, squat, jump squat or power clean at improving CMJ jump height were found to be inconsistent. Moreover, no compelling evidence was found to suggest that between study differences in subject characteristics, training intensity, frequency or volume could explain the inconsistent outcomes. Another potential reason for the inconsistent effects of a given training exercise was then outlined, namely, some individuals may have their CMJ PDFs stressed in a given training exercise while others may not. This is based on the hypotheses that different individuals have the capacity to: (a) have different CMJ PDFs, and (b) experience different training stresses in a given exercise.

The resounding implication of the inconsistent outcomes of training studies examined in this review is that coaches cannot be sure as to which training exercise will be most effective at enhancing their athletes' CMJ jump height. There is a need therefore, for researchers to develop pre-training methods of identifying the training exercise that will most effectively enhance CMJ jump height. In light of this, a biomechanical diagnostic and prescriptive pathway was proposed (Figure 2.9, pg76). Such a pathway may facilitate a pre-training identification of the training exercise that will most effectively enhance a given group's, subgroup's or individual's CMJ jump height. The proposed pathway however requires rigorous testing before it can be recommended for practical use.

Finally, and perhaps of less importance, it is evident that the vast majority of training studies only examine the effect of training on the performance outcome of interest and not on the underlying neuromuscular capacity. Moreover, those studies that have examined the effects of a given training exercise on the underlying neuromuscular capacity have typically done so at a whole body rather than joint level.

Chapter 3

Study 1: An acute investigation of the proposed biomechanical diagnostic and prescriptive pathway

3.1 Introduction

While the drop jump, squat, jump squat and power clean training exercises are each purported to enhance maximal CMJ jump height, there are generally inconsistent findings regarding their effectiveness at doing so (section 2.3, Tables 2.24, 2.30, 2.32 and 2.35, respectively). In addition, there is no overwhelming evidence to suggest that between study differences in subject characteristics, training intensity, frequency or volume can fully explain the inconsistent training outcomes of a given training exercise (section 2.3, Tables 2.24, 2.30, 2.32 and 2.35, respectively).

The theory of training overload states that in order for CMJ jump height to be enhanced, the performance determining factors (PDFs) of the CMJ must be challenged by a training stress at a level beyond which they are accustomed (Zatsiorsky and Kraemer 2006). Such training stress, imposed throughout a training period, should lead to an enhancement in the CMJ PDFs and in turn an enhancement in CMJ jump height. Given the inconsistencies in the response to a given training exercise, the question thus becomes why would a training exercise appropriately stress one individual's CMJ PDFs but not another's? This may be because (a) different individuals have different CMJ PDFs, and\or (b) different individuals experience different acute training stresses while undertaking the same training exercise. Both possibilities are in accordance with the notion that each individual is unique and will possibly possess an individualised neuromusculoskeletal solution (movement strategy) for a given task (Bates 1996; Dufek et al. 1995). While Aragon-Vargas and Gross (1997a) and Bobbert et al. (1986a) provide indirect evidence to support points 'a' and 'b' respectively, it appears that no study has directly examined these hypotheses.

As the outcomes of training studies that have examined the effects of respective training exercises on CMJ jump height are generally inconsistent, a coach cannot be sure as to which training exercise will be most effective at enhancing their athletes' CMJ jump height. Obviously this is not a satisfactory situation, especially when working with elite athletes. It is apparent therefore that researchers must seek to develop pre-training methods of identifying the training exercise that will most effectively enhance an athlete's CMJ jump height. Moreover, cognisant of points 'a' and 'b' above, it is apparent that such methods should consider that different individuals (and thus groups) might have different CMJ PDFs and experience different training stresses when utilising the same training exercise. In light of all of this, a biomechanical diagnostic and prescriptive pathway has been proposed (Figure 2.9 pg77, see section 2.4 for a detailed description).

The proposed pathway may, in theory, be applied to identify the most effective training exercise for a given group or individual using a group or single-subject analysis respectively. Clearly this requires testing both acutely (the current study) and with training studies (studies two and three). In addition, it was noted in section 2.4.2 that limitations inherent with a single-subject analysis may undermine or limit the application of the proposed pathway at an individual subject level. It may therefore be worth applying the proposed pathway using a combination of both a group and subgroup (cluster) analysis. Again this requires testing both acutely (the current study) and with training studies (study two and three).

The aims of the current (acute) research study are:

(1) To examine whether CMJ performance related factors (PRFs)[1] are consistent across individuals or whether individuals have the capacity to possess a unique set of CMJ PRFs.

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[1] While CMJ PDFs are those CMJ parameters that ultimately determine jump height they cannot be identified experimentally in an acute testing session, as a true cause and effect relationship cannot be established. Instead, CMJ PRFs are identified on the assumption that they are likely to be CMJ PDFs. CMJ PRFs are those CMJ parameters that are significantly correlated with CMJ jump height (see section 2.2.2 for more details).

(2) To examine whether the acute training stress experienced by CMJ kinetic and kinematic parameters in a given exercise is consistent across individuals or whether it may be subject to inter-individual variation.

(3) To identify, using the proposed pathway (steps 1-3), which of the following exercises is likely to be the most effective at improving the group's, or a given individual's, CMJ jump height: drop jump, jump squat, squat or power clean.

(4) To examine whether a subgroup (or subgroups) of individuals can be identified for whom the training exercise selected as being the most effective for the group may not be the most effective to enhance that subgroup's CMJ jump height.

The hypotheses of the current study are:

(1) Individuals will have the capacity to possess a unique set of CMJ PRFs.

(2) The training stress experienced by CMJ parameters in a given exercise will have the potential to vary across individuals.

(3) The proposed pathway will be able to identify the training exercise that is most likely to enhance the group's, or a given individual's, CMJ jump height.

(4) A subgroup (or subgroups) of individuals may exist for whom the training exercise deemed most suitable for the group may not be the most effective exercise to enhance their CMJ jump height.

3.1.1 Delimitations

Before applying the proposed biomechanical pathway to comprehensively identify the most appropriate exercise to use to enhance CMJ jump height it would be necessary to firstly identify the optimal training load for each exercise under examination. Unfortunately, there is little consensus regarding the optimal training load for the respective training exercises examined in this study (Bobbert 1990; Young and Bilby 1993; Cormie et al. 2007a; Bevan et al. 2010). In light of this, the current study specifically examined each training exercise using a training intensity commonly used in training.

3.2 Methodology

3.2.1 Subjects

Twenty-six injury free athletic male adults (mean ± *SD*: age, 22 ± 4 years; weight 77.8 ± 9.8kg) were recruited from students at Dublin City University. All the participants competed for Dublin City University in a sport that involved a jump (most commonly gaelic football, gaelic hurling and basketball). In addition each participant had previously utilised the squat, jump squat, drop jump and power clean training exercises as part of a resistance training routine. The participants were not homogenous in terms of sports participation, training history or jumping ability, but this was considered acceptable, as a degree of inter-individual heterogeneity is required to identify CMJ PRFs using correlation analysis. Moreover, the heterogeneity of subjects was taken into consideration in this study with the use of a single-subject analysis After the nature and risks of the study were explained each participant gave a written informed consent as required by the University Ethics Committee.

3.2.2 Experimental protocol

While the participants had previously utilised the squat, jump squat, drop jump and power clean in training, some had not undertaken one or more of these exercises within the previous three months. In light of this, it was deemed appropriate to run a four week re-familiarisation period before testing where each participant carried out two sets of eight repetitions of each training exercise and the countermovement jump (CMJ). The lead researcher, a certified strength and conditioning specialist (NSCA CSCS), supervised each session and exercise instruction was provided where appropriate. The load used in the training exercises was low in the first two weeks of the familiarisation sessions but gradually increased in weeks three and four (see Table 3.1).

Table 3.1 Training exercise loads used during the familiarisation period

	Weeks 1-2	Week 3	Week 4
Squat	50% 1RM	50% 1RM	60% 1RM
Jump squat	10% 1RM squat	15% 1RM squat	20% 1RM squat
Drop jump	15cm	20cm	30cm
Power clean	30% 1RM	40% 1RM	50% 1RM

Following the familiarisation period each subject's one repetition maximum (1RM) for the squat and five repetition maximum (5RM) for the power clean was established using standardised testing procedures described by Baechle and Earle (2000) (pp 409, Figure 18.1). Both tests were carried out on different days separated by at least 48 hours. Participants were asked to refrain from lower body lifting or any strenuous activity for 48 hours before each test. A 5RM test was considered safer for the power clean than a 1RM test, as spotters cannot be utilised during this exercise. During the 5RM, if a participant's technique deteriorated to such an extent that there was a substantially increased risk of injury the test was stopped and that attempt deemed unsuccessful. An estimated 1RM power clean was subsequently established for each subject using data provided by Baechle and Earle (2000) (pg 410-411, Table 18.8).

During the familiarisation sessions it was observed that participants did not use a fully parallel squat (top of thigh parallel to floor) while squatting. Indeed many found it 'unnatural' to squat to such a depth and maintained that they would not do so during typical training sessions. It was therefore decided to carry out the 1RM squat tests using a squatting depth more familiar to the current participants rather than a parallel squat. To facilitate this, squats produced by a subset of individuals were analysed and peak internal knee flexion angles were obtained. It was found that the subjects on average produced knee angles of 100° (see Figure 3.1) while squatting. In light of this subjects were familiarised with squatting to a depth equivalent to a knee angle of 100° before the 1RM testing began and were instructed to squat to this depth during testing. To familiarise each subject with the required squatting depth each subject squatted (using an unweighted barbell) to the desired knee angle (checked with a goniometer) and the depth of the barbell in this position was marked on a metal pole placed alongside the squatter. The subject was then instructed to squat normally, while verbal feedback was given so that the subject squatted to the desired depth (the depth where the barbell reached the mark on the pole). After a couple of repetitions all subjects, including those who had previously been able to squat to parallel, were able to comfortably and consistently squat to the desired depth. The same mark was also used to check that the subject squatted to the correct depth during the 1RM testing. As each participant could comfortably carry out the CMJ, the drop jump, the jump squat and the power clean in the way in which athletes are commonly instructed to do so (see sections 2.2.1, 2.3.4, 2.3.5 and 2.3.6 respectively), it was not necessary to alter the participant's technique in these movements.

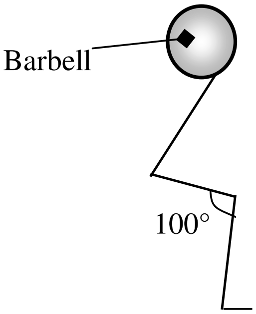

Figure 3.1 Typical participant body orientation at the low point of the squat

A biomechanical analysis of each subject's CMJ, drop jump, squat, jump squat and power clean was carried out within one week of the strength tests described above. Subjects were asked to refrain from any strenuous activity for 48 hours before the laboratory test. A standard warm-up routine, consisting of low intensity jogging, stretching and three sub-maximal trials of the CMJ and each exercise under examination, preceded the testing. For the actual testing, each participant performed fifteen CMJ trials and five trials of each respective training exercise. The trials were performed with feet approximately shoulder width apart and with each foot on an independent force platform. Feet were kept parallel with the x-axis of the force platform, restricting motion to the sagittal plane as much as possible. Subjects wore brief shorts and their own athletic shoes. The CMJ and training exercises were carried out as previously described (see sections 2.2.1, 2.3.3, 2.3.4, 2.3.5 and 2.3.6) and the specific instructions given to subjects are detailed in Table 3.2. No additional instructions were given to insure self-selection of technique and minimise any investor-induced bias into the experiment. Each training exercise was analysed at a training load that is typically used when training to improve CMJ jump height. These loads were: 30cm in the drop jump (Young et al. 1999), 30% 1RM squat in the jump squat (Wilson et al. 1993), 80% 1RM squat in the squat (Wilson et al. 1996) and 75% 1RM power clean in the power clean (Channell and Barfield 2008). Adequate rest was permitted between all repetitions of the same exercise, 30 seconds between repetitions of both the CMJ and drop jump and one minute between repetitions of each of the other exercises. Previous studies have utilised similar between trial rest periods (Read and Cisar 2001; Enoka 1998; Cormie et al. 2008) After completing all the required repetitions of a given exercise subjects rested for three minutes before moving on to the next exercise of interest. Participants were informed that they could take additional recovery time between exercises if required but none felt it necessary to do so. CMJs were always performed first,

Table 3.2 Training exercise instructions

CMJ	Countermove to a self selected depth then jump as high as possible (Bobbert et al. 1987a).
DJ	Perform a DJ for maximal jump height while attempting to minimise ground contact time (Matavulj et al. 2001).
Squat	Squat to a 100 degree knee angle (in a slow and controlled manner) then as forcefully as possible lift the weight upwards (Young and Bilby 1993). Do not allow the heels to leave the floor at the end of the upward movement (Young and Bilby 1993).
JS	Countermove to a self selected depth then jump as high as possible (Baker et al. 2001). Keep constant downward pressure on the barbell throughout the jump (Cormie et al. 2007b).
PC	Perform the lift as explosively as possible with proper technique while attempting to minimise the use of the arms to lift the barbell (Earle and Baechle 2000).

DJ = drop jump; JS = jump squat; PC = power clean but the order that the training exercises were completed was randomised. In both the CMJ and drop jump hands were placed on the hips to prevent the use of the arms (Vanrenterghem et al. 2008). The subjects placed the barbell in a squat rack between repetitions of both the squat and jump squat. In the power clean the bar was placed on stands before the commencement of every trial so that the bar was consistently 23cm from the ground for all subjects (Enoka, 1988).

3.2.3 Data acquisition

Five spherical reflective markers were placed bi-laterally at the following anatomical landmarks: fifth metatarsal joint, lateral malleolus, lateral femoral epicondyle, greater trochanter and the glenohumeral joint. These markers were used to map the motion of the joint centre of the metatarsophalangeal, ankle, knee, hip and shoulder joints, respectively. In addition, a marker was placed on both heels, in line with the toe marker. During the squat and jump squat the shoulder markers obstructed barbell placement so in these exercises the markers were moved from the shoulder and placed at either end of the barbell. Markers were fixed to the skin\footwear\barbell using double-sided tape.

A VICON motion analysis (VICON 512 M, Oxford Metrics Ltd, England) system was used in conjunction with two AMTI force platforms mounted in the ground (BP-600900, AMTI, MA, USA) and an AMTI amplifier. VICON software (Workstation) controlled simultaneous collection of motion and force data at 250Hz. Twelve cameras placed evenly around the sampling area emitted infrared light from diode stroboscopes in each camera, which was reflected back to the cameras by the spherical markers. Two-dimensional co-ordinate data was calculated for each camera and subsequently three-dimensional co-ordinate data for the captured motion was calculated by direct linear transformation (VICON v4.6, Oxford Metrics Ltd, England).

Raw co-ordinate data and force data were exported to Microsoft Office Excel (version 9.0, Microsoft Corporation, U.S.A) and subsequently applied to a number of specially designed in-house computer programs developed by the author. The data was filtered using a recursive second-order low pass Butterworth digital filter (Winter, 1990). The force plate data was filtered at 70Hz and marker position data at different values: toe 6.62Hz, heel 6.62Hz, ankle 7.52Hz, knee 9.21Hz, hip 8.50Hz and shoulder 6.64Hz (Moran 1998).

3.2.4 Data analysis

From the three-dimensional position of the markers, a two-dimensional (sagittal plane) four-segment model, linked by frictionless hinge joints, was defined (Figure 3.2). Bi-lateral marker data was combined in the formation of the model. The four-segment model has been used in previous jumping (Vanrenterghem et al. 2008; Moran and Wallace 2007) and squatting studies (Fry et al. 2003). The four segments were the foot, shank, thigh and head-arms-trunk (HAT) separated by the ankle, knee and hip joints, respectively.

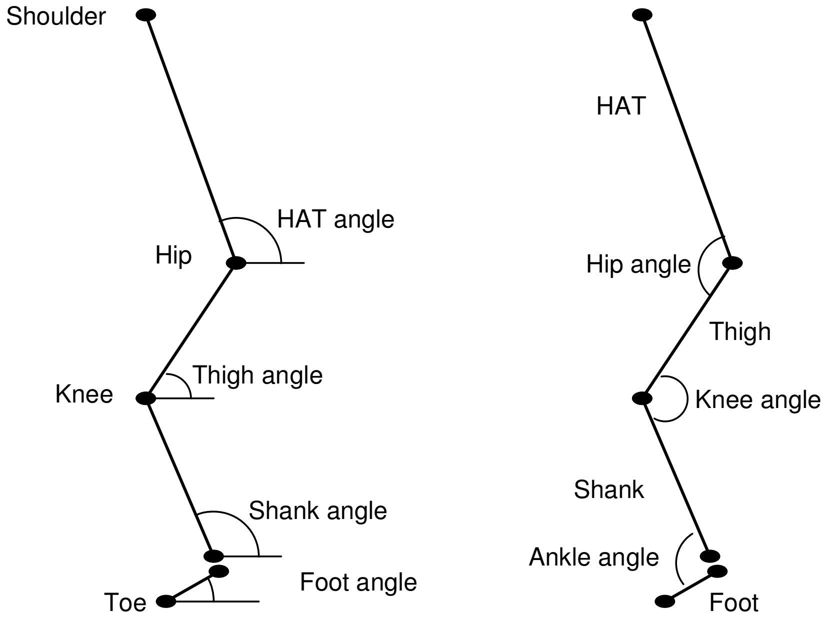

Figure 3.2 Graphical representation of body segments and angle conventions

The eccentric and concentric phases of the CMJ, drop jump, jump squat and squat were defined with respect to whole body power production and the position of the body's centre of mass (COM). The eccentric phase started with the initiation of negative power production and ended when negative power production reduced to zero and the body's COM was at minimum height. The concentric phase began with the initiation of positive power production and ended, for the jumps, when the toes lost contact with the force platform, and for the squat when the body's COM returned to starting height. For the power clean, only the second pull phase of the lift was analysed. The second pull is the portion of the power clean that most closely resembles the thrust phase of the CMJ (Garhammer 1993). The start of the second pull was defined as the instant the knee joint resumed extension following the brief flexion of the transition phase. . The end of the second pull was defined as the instant that the body's COM reached its highest point.

The vertical height of the body's COM (Y_{COM}) was calculated as:

$$Y_{COM} = \sum_{s=1}^{n=4} (R_i * YCOM_i) \qquad \text{[Equation 3.1]}$$

Where:

R_i was the ratio of segment weight to whole body weight (Table 3.1, pp56-57, Winter 1990).
$YCOM_i$ was the vertical height of the COM of segment i.

CMJ jump height was calculated according to Vanrenterghem et al. (2001) as the difference between the body's COM position when standing and at the apex of the jump.

Segment angles were calculated in an anti-clockwise direction from the right horizontal with the distal end point of the segment as the origin (Figure 3.2). The segment angles were defined as θ_{foot}, θ_{shank}, θ_{thigh} and θ_{HAT} (Figure 3.2). Joint angles, θ_{ankle}, θ_{knee}, θ_{hip}, were subsequently calculated as the angle between adjacent segments, with smaller joint angles indicating a more flexed joint and greater joint angles indicating a more extended joint.

$$\theta_{ankle} = 3.1416 - \theta_{shank} + \theta_{foot} \qquad \text{[Equation 3.2]}$$

$$\theta_{knee} = 3.1416 - \theta_{shank} + \theta_{thigh} \qquad \text{[Equation 3.3]}$$

$$\theta_{hip} = 3.1416 - \theta_{HAT} + \theta_{thigh} \qquad \text{[Equation 3.4]}$$

Vertical velocity of the body's COM and angular velocities of the hip, knee and ankle joints, were obtained by differentiating COM and joint angular displacement data respectively, using the finite difference procedure (Moran and Wallace 2007).

Whole body amplitude of movement in the CMJ, drop jump, squat and jump squat was calculated as the difference between the body's COM position when standing and that at its low point at the end of the countermovement (Bobbert et al. 1986). Whole body amplitude of movement in the power clean was defined as the difference between the body's COM position at the start and end of the second pull.

Ground reaction force data was measured directly by two force platforms (one for each foot), the data from which were combined. Whole body power was calculated as the product of the vertical velocity of the body's COM and vertical ground reaction force (Cormie et al. 2009) and whole body impulse as the integral of force with respect to time.

Concentric rate of force development (RFD) was calculated as the rate of vertical ground reaction force development from the initiation of the concentric phase to the point at which peak force occurred [equation 3.5] (Cormie et al. 2009).

$$\text{Concentric RFD} = \frac{\text{Peak vGRF - vGRF at } t_{\text{ConStart}}}{\Delta t} \qquad \text{[Equation 3.5]}$$

Where:

t_{ConStart} is the time at which the concentric phase began

Δt = time difference between the start of the concentric phase and peak concentric force

vGRF = vertical ground reaction force

RFD at the start of the concentric phase may be of particular relevance to jump height (Bobbert et al. 1996) but the measure of RFD outlined in equation 3.5, might not be sensitive enough to examine it. An additional measure of concentric

RFD, initial concentric RFD, was therefore calculated (equation 3.6). Initial RFD was calculated over six data points, that is, 0.024 seconds.

$$\text{Initial concentric RFD} = \frac{\text{vGRF after 0.024s} - \text{vGRF at } t_{\text{ConStart}}}{\text{0.024s}} \qquad \text{[Equation 3.6]}$$

Where:

t_{ConStart} is the time at which the concentric phase began
vGRF = vertical ground reaction force

Concentric rate of power development (RPD) and initial concentric RPD were calculated using equations 3.5 (Cormie et al. 2009) and 3.6 with the relevant power and time values.

Whole body eccentric stiffness was calculated as the ratio of change in eccentric vGRF to the simultaneous change in the amplitude of the body's COM (Moir et al 2009; Hunter and Marshall 2002).

$$\text{Eccentric stiffness} = \frac{\text{Peak vGRF} - \text{vGRF at } t_{\text{EccStart}}}{\text{Amplitude of the body's COM}} \qquad \text{[Equation 3.7]}$$

Where:

t_{EccStart} is the time at the start of the eccentric phase
vGRF = vertical ground reaction force

Joint and segment kinetics were calculated using standard inverse dynamics, combining kinematic and ground reaction force data with anthropometric data (Table 3.1, pp56-57, Winter 1990). Net joint reaction forces were calculated as follows.

$$Fxp = (Mass * Ax) + Fxd \quad [Equation\ 3.8]$$

$$Fyp = (Mass * Ay) + Fyd + (m*g) \quad [Equation\ 3.9]$$

Where:

Fxp, Fyp = proximal joint reaction force in the x or y direction
Fxd, Fyd = distal joint reaction force in the x or y direction
Ax, Ay = acceleration in x or y direction
m = mass of segment
g = acceleration due to gravity

Net joint moments were calculated as follows.

$$Mp = Md + (Fxd * d1) + (Fxp * d2) + (Fyd * d3) + (Fyp * d4) + I\alpha$$
[Equation 3.10]

Where:

Mp = joint moment at proximal end
Md = joint moment at distant end
I = moment of inertia
α = segment angular acceleration

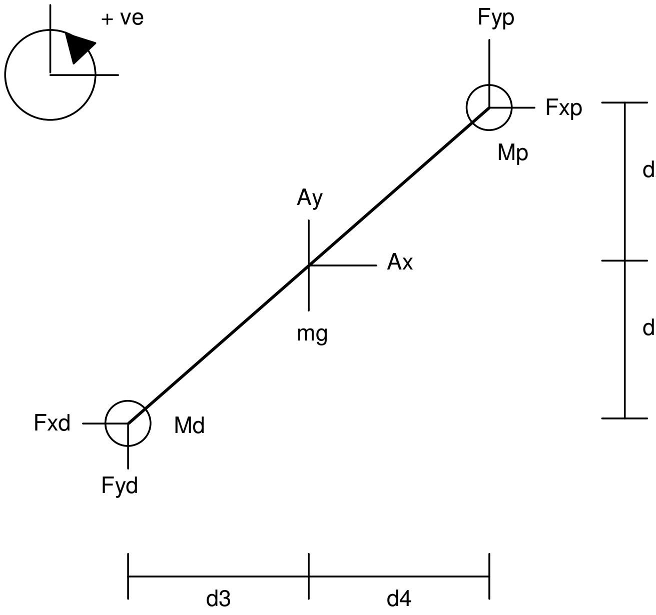

Figure 3.3 Free body diagram for generic body segment

Joint extensor moments were defined as positive and flexor moments were defined as negative (Aragon-Vargas and Gross 1997b). Net joint power was calculated as the dot product of net joint moment and joint angular velocity (Moran and Wallace 2007). Work done at each joint was calculated from the integral of power with respect to time using the Trapezoidal rule (Equation 4.0) [Moran and Wallace 2007]. In order to calculate both positive and negative work, care was taken to integrate between the appropriate time epochs. Whole body work done during the concentric and eccentric phase was calculated by summing the work done at the hip, knee and ankle during these respective phases.

$$\text{Work done} = \sum [(P_i + P_{i+1})/2] * \Delta t \qquad \text{Equation 3.11}$$

Where:

P_i = angular power at point ‘i’

Δt = time between adjacent samples (0.004s)

Joint rate of moment development and RPD were calculated in the same way as whole body RFD and RPD (equations 3.5 and 3.6), using the appropriate joint moment and power values respectively. Similarly, eccentric joint stiffness was calculated in the same way as whole body eccentric stiffness (equation 3.7), using the appropriate joint moment values.

Body weight was included in the calculations of all kinetic variables for the CMJ and drop jump while system weight (barbell weight plus body weight) was included in the calculation of all kinetic variables for the squat, jump squat and power clean (Cormie et al. 2007a).

3.2.5 Variables analysed

This section outlines the variables analysed for the CMJ in (a) the concentric phase, and (b) the eccentric phase. Unless otherwise stated each variable was analysed for each training exercise under examination. All kinetic variables were normalised to body mass (Lees et al. 2004).

(a) Concentric phase variables

The following kinetic variables were analysed at both a whole body and joint level: peak force, peak power, work done, rate of force development, initial rate of force development (during first 0.024s of the concentric phase), rate of power development and initial rate of power development (during first 0.024s of the concentric phase) (Cormie et al. 2009; Cormie et al. 2008; Aragon-Vargas and Gross 1997b; Bobbert et al. 1987a; Wretenberg et al. 1996; Kawamori et al. 2005; Enoka 1988).

The following kinematic variables were analysed: amplitude of the body's COM, joint angles at joint reversal (indicative of joint ROM), duration of the concentric phase and the time between peak power and takeoff (Harman et al. 1990; Aragon-Vargas and Gross 1997b; Escamilla et al. 2001b; Cormie et al. 2008; Bobbert et al. 1987a). Joint angles at the start of the second pull in the power clean were calculated instead of joint angles at joint reversal. Of note, as neither the power clean nor the squat involve a takeoff, the time between peak power and takeoff was not calculable for these exercises.

Coordination was analysed by examining the time delay between key events at adjacent joint pairings: hip and knee; knee and ankle. The following variables were examined: joint reversal (Rodacki et al. 2002), peak joint moment (Jones and Caldwell 2003) and peak joint power (Rodacki et al. 2002).

(b) Eccentric phase variables

The following kinetic variables were analysed at both a whole body and joint level: force at COM\joint reversal, peak power, work done and stiffness. Force at COM\joint reversal was calculated as it is at, or close to, this instant that peak eccentric force occurs. Whole body COM negative impulse was also calculated (Bobbert et al. 1986; Harman et al. 1990; Moran and Wallace 2007; Hunter and Marshall 2001). The kinematic variables analysed were whole body peak negative vertical velocity (Dowling and Vamos 1993) and the duration of the eccentric phase (Bobbert et al. 1986).

Dowling and Vamos (1993) suggest that a ratio of negative and positive impulse may provide a more sensitive variable to quantify the optimal loading for stretch-shortening cycle utilisation. In light of this, a ratio of impulse at the start of the concentric phase (first 0.056s) to that at the end of the eccentric phase (last 0.056s) was calculated. Similar ratios were calculated for eccentric and concentric work done at both the whole body and joint level.

As only the second pull phase of the power clean was investigated no eccentric variables, or eccentric\concentric ratios were analysed for the power clean.

3.2.6 Statistical analysis

To investigate aims one and two of the current study the required statistical procedures were carried out using a single-subject analysis. Aim one of the current study was to examine whether CMJ PRFs are consistent across individuals or whether each individual may have the capacity to possess a unique set of CMJ PRFs. To identify an individual's CMJ PRFs Pearson product moment correlations were carried out between the CMJ jump height achieved (across each individual's 15 CMJ trials) and all 63 biomechanical parameters outlined in section 3.2.5. All data was screened for outliers before the correlations were carried out (Vanrenterghem et al. 2008) and an $\alpha = 0.05$ level was adopted for statistical significance. To screen each individual's data for outliers, parameter magnitude values (for all 15 trials) were converted to z-scores. A parameter magnitude with a z-score greater than 3.29 was considered an outlier (Field, 2000) and that data point was removed. Those CMJ parameters that were significantly correlated with jump height were deemed to be CMJ PRFs. Visual examination of the scatter plots of each parameter and jump height was undertaken to determine if a linear/non-linear relationship was present and to check for the presence of outliers.

Aim two of the current study was to examine if the training stress experienced by CMJ parameters in a given exercise could vary across individuals. To investigate this, the extent to which a given parameter's magnitude in the CMJ differed to its magnitude in a training exercise was identified for each of the twenty-six participants. Data from the first five CMJ trials and from the five trials of the respective training exercises was used in this analysis. Independent t-tests were employed to test for statistical differences and an $\alpha = 0.05$ was adopted for statistical significance. An independent t-test was used as opposed to a dependent t-test as several authors have highlighted that the use of repeated-measures techniques in a single-subject analysis is inappropriate (Dufek and Zhang 1996; Bates et al. 2004). For example, the use of a repeated measures technique in the current application would assume that data from trial one of the CMJ is correlated with data from trial one of a given training exercises, which is not the case. Bates et al. (2004) suggest that for single-subject analysis the most appropriate approach is to assume that trial values are independent and to use the corresponding independent test procedure.

Aim three of this study was to utilise steps 1-3 of the proposed pathway (Figure 2.9) to identify which of the examined exercises (drop jump, jump squat, squat or power clean) was likely to be the most effective at improving the group's, or a given individual's, CMJ jump height. To achieve this the proposed pathway was applied using both a group and single subject analysis, respectively. Details on how the pathway was applied at the group level will be outlined first followed by details on how the pathway was applied at the individual subject level.

Step one of the proposed biomechanical pathway involves the identification of the group's CMJ PRFs (see Figure 2.9, pg77). This was achieved by performing Pearson product moment correlations between the CMJ jump height achieved and each of the 63 biomechanical parameters outlined in section 3.2.5. The mean data from each individual's best three jumps was used (Stephens et al. 2007), and all data was screened for outliers before the correlations were carried out (Vanrenterghem et al. 2008). Those parameters that were significantly correlated with jump height ($p<0.01$) were deemed to be group level CMJ PRFs. Visual examination of the scatter plots of each parameter and jump height was undertaken to determine if a linear relationship was present and to check for the presence of outliers. The significance level adopted in this analysis (α = 0.01) was more stringent than that typically used (α = 0.05) in order to increase the likelihood that identified CMJ PRFs were true CMJ PDFs (see section 2.2.2 for more details on the distinction between PRFs and PDFs). Ashley and Weiss (1994) also used a significance level of α = 0.01 when calculating Pearson correlations between jump height and several (56) independent variables.

Step two of the proposed pathway involves the identification of the acute training stress experienced by each CMJ PRF in each training exercise and a comparison of the stress experienced by each CMJ PRF across the different exercises (see Figure 2.9, pg77). This was achieved through the use of a repeated measures analysis of variance with Bonferroni post hoc analysis (Cormie et al. 2008). An α = 0.05 level was adopted for statistical significance. When the magnitude of a kinetic CMJ PRF was greater in a training exercise than it was in the CMJ, that parameter was said to have experienced an appropriate acute training stress [Table 3.3] (Bobbert et al. 1987a). Additionally, when the magnitude of a kinetic CMJ PRF was significantly smaller in a training exercise in comparison to the CMJ, or there was no statistical difference, the parameter was deemed to have experienced no acute training stress [Table 3.3] (Bobbert et al. 1987). It has been suggested that technique and coordination based CMJ PRFs can also experience training stress in a given exercise (see section 2.3.1, pg32). Technique and coordination based CMJ PRFs are different to kinetic CMJ PRFs in that they can experience a training stress when their magnitudes are significantly smaller in a training exercise in comparison to the CMJ. In addition, kinematic CMJ PRFs may experience an inappropriate acute training stress (see section 2.3.1, pg32). The criteria used to identify the nature of the acute training stress experienced by kinematic CMJ PRFs are outlined in Table 3.4.

Table 3.3 Identifying the acute training stress experienced by kinetic CMJ PRFs

CMJ and exercise comparison	CMJ PRF
Exercise magnitude > CMJ magnitude	Appropriate training stress
CMJ magnitude > Exercise magnitude	No training stress
No difference between CMJ and exercise magnitudes	No training stress

Table 3.4 Identifying the acute training stress experienced by kinematic CMJ PRFs

CMJ and exercise comparison	Positively correlated kinematic CMJ PRF	Negatively correlated kinematic CMJ PRF
Exercise magnitude > CMJ magnitude	Appropriate training stress	Inappropriate training stress
Exercise magnitude < CMJ magnitude	Inappropriate training stress	Appropriate training stress
No difference between CMJ and exercise magnitudes	No training stress	No training stress

Step three of the proposed pathway (see Figure 2.9, pg77) involves the identification of the expected post-training changes that CMJ PRFs will experience following training with a given exercise, and a comparison of these expected post-training changes across training exercises. Bobbert et al. (1986a) hypothesise that the application of an appropriate training stress to CMJ kinetic parameters over the course of a training period is likely to induce a training effect and lead to enhancements in the magnitude of these same parameters. Based on this hypothesis (which is tested in study two) CMJ kinetic parameters that experienced an acute pre-training stress in a given training exercise were expected to increase following a training period. Conversely, kinetic CMJ PRFs that experienced no training stress were not expected to change following a training period. The same post-training outcomes were expected for kinematic CMJ PRFs, but in addition, those kinematic CMJ PRFs that experienced an inappropriate training stress were expected to experience a post-training decline.

Bobbert et al. (1987a) suggest that when one training exercise imposes a greater training stress on CMJ parameters than another, it will in turn induce a greater post-training magnitude change in these parameters. Based on this hypothesis, a training exercise that stressed a CMJ PRF to a greater extent than another was expected to induce a greater post-training magnitude change in that CMJ PRF.

Applying the proposed pathway at the individual subject level requires following the same steps taken at the group level, but doing so using single-subject statistical procedures. Step one of the proposed pathway involved identifying an individual's CMJ PRFs and this was done using the same single-subject procedures outlined above for aim one. Step two of the proposed pathway involved the identification of the acute training stress experienced by an individual's respective CMJ PRFs in each exercise, and a comparison of the stress experienced by each CMJ PRF across the different exercises. This was achieved through the use of an independent analysis of variance with Bonferroni post hoc analysis. Data from the first five CMJ trials and from the five trials of each of the training exercises examined was used in this analysis. An $\alpha = 0.05$ level was adopted for statistical significance. The nature of the training stress experienced by the CMJ PRFs (appropriate, inappropriate or no training stress) was identified in the same way as that described above at the group level (see Tables 3.3 and 3.4). As at the group level, appropriate training stresses were expected to lead to post-training CMJ PRF enhancements, inappropriate training stresses to lead to post-training CMJ PRF declines and no training stress to lead to no post training CMJ PRF magnitude changes.

Aim four of the current study was to examine whether a subgroup (or subgroups) of individuals could be identified for whom the training exercise selected as being the most effective for the group may not be the most effective to enhance the subgroup's CMJ jump height. To investigate this, individuals were subgrouped based on the magnitude of pre-training stress that CMJ PRFs (group level CMJ PRFs) experienced in the given training exercise (PRF magnitude in exercise – PRF magnitude in CMJ). A hierarchical agglomerative cluster analysis, the Ward's linkage method with a squared euclidean distance measure, was used to subgroup individuals (Park et al. 2005). The mean data from each individual's best three jumps was used in the analysis and all data was standardised (converted to z-scores) before being clustered. No standard, objective selection procedure exists in the selection of how many subgroups should be formed (Hair et al. 1987). Some authors have used the change in agglomeration coefficient at a particular stage in the clustering process to determine the appropriate number of subgroups (Kinsella and Moran 2008; Park et al. 2005), and this approach was used in the current study. A large change in the agglomeration coefficient means that heterogeneous clusters are being combined (Park et al. 2005). The number of subgroups chosen was validated with a multivariate ANOVA (MANOVA) that identified if significant between subgroup differences existed in the magnitude of experienced acute training stress and an $\alpha = 0.05$ level was adopted for statistical significance. Kinsella and Moran (2008) acknowledged that clustering techniques are very sensitive to variables that are highly correlated with each other. In the current study the CMJ PRFs used for clustering were assessed for inter-correlations and when a large correlation was found ($r \geq 0.70$ i.e. greater than 50% common variance) one of the pair of inter-related CMJ PRFs, the one with the lowest correlation with jump height, was removed from the analysis. It was hoped that such an exclusion criteria would protect against the problems of including highly inter-related variables in a cluster analysis but also reduce the risk of losing important data with which to cluster individuals.

Finally, the training stress experienced by each CMJ PRF (appropriate, inappropriate or no training stress) in each respective subgroup was identified using dependent t-tests (CMJ magnitude versus exercise magnitude).

All the statistical analyses described above were carried out using SPSS for Windows (version 15.0, SPSS Inc., U.S.A).

3.3 Results

The first aim of this study was to examine whether CMJ PRFs are consistent across individuals or whether individuals have the capacity to possess a unique set of CMJ PRFs. Tables 3.5-3.9 detail the CMJ PRFs identified for five representative individuals, A-E respectively. Individual A was considered the best jumper (55.9cm), Individual E the worst (34.8cm) and individuals B, C and D, good, average and poor jumpers respectively. To provide further evidence that individuals have the capacity to possess different CMJ PRFs, Table 3.10 details the number of individuals who had a group level CMJ PRF (see group analysis to follow) as a CMJ PRF at the individual subject level.

Table 3.5 Individual A's CMJ PRFs

Jump height (M ± SD) = 55.9 ± 1.5cm

CMJ PRFs	r	p
Concentric phase duration *	-0.81	<0.01
Whole body concentric RPD	0.74	<0.01
Hip concentric peak power	0.70	<0.01
Time between peak power and takeoff *	-0.68	<0.01
Amplitude of the COM *	-0.66	0.01
Knee angle at joint reversal	0.66	0.01
Whole body concentric peak power	0.64	0.01
Ankle moment at joint reversal	0.63	0.01
Hip concentric work done	0.60	0.02

CMJ PRF negatively correlated with jump height means a smaller magnitude was associated with larger jump heights

Table 3.6 Individual B's CMJ PRFs

Jump height (M ± SD) = 51.4 ± 1.5cm

CMJ PRFs	r	P
Hip concentric Peak moment	0.79	<0.01
Hip concentric Peak power	0.69	<0.01
Time between peak power and takeoff *	-0.68	0.01
Whole body concentric peak power	0.65	0.01
Ankle RMD at the start of the concentric phase	0.65	0.01
Ankle concentric RPD	0.64	0.01
Hip eccentric Peak power	0.62	0.01
Knee concentric RPD	0.61	0.02
Ratio of early ankle concentric work done to late ankle eccentric work done	0.61	0.02
Time between peak moment at the hip and knee *	-0.55	0.03

CMJ PRF negatively correlated with jump height means a smaller magnitude was associated with larger jump heights

Table 3.7 Individual C's CMJ PRFs

Jump height (M ± SD) = 45.5 ± 1.3cm

CMJ PRFs	r	p
Hip concentric peak moment	0.71	<0.01
Hip eccentric work done	0.62	0.02
Hip RPD at the start of the concentric phase	0.61	0.02
Ankle eccentric Peak power	0.56	0.04
Hip moment at joint reversal	0.56	0.04

CMJ PRF negatively correlated with jump height means a smaller magnitude was associated with larger jump heights

Table 3.8 Individual D's CMJ PRFs

Jump height (M ± SD) = 41.7 ± 0.9cm

CMJ PRFs	r	p
Hip concentric peak power	0.76	<0.01
Ratio of early hip concentric work done * to late hip eccentric work done *	-0.75	<0.01
Whole body concentric peak power	0.69	<0.01
Whole body eccentric peak vertical velocity	0.68	0.01
Whole body eccentric impulse	0.66	0.01
Hip concentric peak moment	0.65	0.01
Whole body concentric peak force	0.64	0.01
Whole body concentric work done	0.63	0.01
Whole body eccentric peak power	0.63	0.01
Knee concentric peak power	0.61	0.02

CMJ PRF negatively correlated with jump height means a smaller magnitude was associated with larger jump heights

Table 3.9 Individual E's CMJ PRFs

Jump height (M ± SD) = 34.8 ± 0.7cm

CMJ PRFs	r	p
Whole body RPD at the start of the concentric phase	0.66	0.01
Concentric phase duration *	-0.64	0.01
Knee eccentric work done	0.55	0.03

CMJ PRF negatively correlated with jump height means a smaller magnitude was associated with larger jump heights

Table 3.10 The number of individuals who had a group level CMJ PRF as a CMJ PRF at the individual subject level

	Positively correlated CMJ PRF	Negatively correlated CMJ PRF	Not a CMJ PRF
Whole body concentric peak power	7	0	19
Whole body concentric work done	6	0	20
Ankle concentric peak power	2	0	24
Time between peak power and takeoff	0	13	13
Hip concentric peak power	8	0	18
Knee concentric work done	2	0	24
Amplitude of the centre of mass	0	0	26
Knee concentric peak power	1	0	25

The second aim of this study was to examine whether the acute training stress experienced by CMJ kinetic and kinematic parameters in a given exercise is consistent across individuals or whether it may be subject to inter-individual variation. To investigate this, the extent to which a given parameter's magnitude in the CMJ differed to its magnitude in a training exercise was examined for all twenty-six participants. Table 3.11 details the number of individuals who experienced a significant difference (or no difference) for a given parameter in each training exercise. The twelve parameters presented in Table 3.11 represent the different types of biomechanical variables investigated in this study, that is, kinetic and kinematic variables at the whole body and joint level.

Table 3.11 The number of individuals who experienced significant differences between a parameters magnitude in the CMJ vs. the DJ\JS\Squat\PC

	Whole body concentric peak power			Hip concentric peak power			Knee concentric peak power			Ankle concentric peak power		
Exercise	Ex<CMJ ($p<0.05$)	No Sig. Diff.	Ex>CMJ ($p<0.05$)	Ex<CMJ ($p<0.05$)	No Sig. Diff.	Ex>CMJ ($p<0.05$)	Ex<CMJ ($p<0.05$)	No Sig. Diff.	Ex>CMJ ($p<0.05$)	Ex<CMJ ($p<0.05$)	No Sig. Diff.	Ex>CMJ ($p<0.05$)
DJ	0	7	19	8	18	0	0	14	12	2	14	10
JS	26	0	0	17	9	0	8	17	1	1	20	5
Squat	26	0	0	26	0	0	26	0	0	26	0	0
PC	25	1	0	2	6	18	25	1	0	24	2	0
	Whole body concentric peak force			Hip concentric peak moment			Knee concentric peak moment			Ankle concentric peak moment		
Exercise	Ex<CMJ ($p<0.05$)	No Sig. Diff.	Ex>CMJ ($p<0.05$)	Ex<CMJ ($p<0.05$)	No Sig. Diff.	Ex>CMJ ($p<0.05$)	Ex<CMJ ($p<0.05$)	No Sig. Diff.	Ex>CMJ ($p<0.05$)	Ex<CMJ ($p<0.05$)	No Sig. Diff.	Ex>CMJ ($p<0.05$)
DJ	0	2	24	2	13	11	0	3	23	0	10	16
JS	0	1	25	0	10	16	0	8	18	0	12	14
Squat	2	7	17	0	3	23	0	7	19	10	14	2
PC	10	9	7	0	0	26	0	9	17	5	9	12
	Amplitude of the COM			Hip angle at joint reversal †			Knee angle at joint reversal †			Ankle angle at joint reversal †		
Exercise	Ex<CMJ ($p<0.05$)	No Sig. Diff.	Ex>CMJ ($p<0.05$)	Ex<CMJ ($p<0.05$)	No Sig. Diff.	Ex>CMJ ($p<0.05$)	Ex<CMJ ($p<0.05$)	No Sig. Diff.	Ex>CMJ ($p<0.05$)	Ex<CMJ ($p<0.05$)	No Sig. Diff.	Ex>CMJ ($p<0.05$)
DJ	21	5	0	0	2	24	2	11	13	4	16	6
JS	17	7	2	1	1	24	4	13	9	3	17	6
Squat	9	6	11	5	6	15	15	6	5	1	6	19

CMJ = countermovement jump; DJ = drop jump; JS = jump squat; PC = power clean; Ex = exercise

† Greater angles at joint reversal represent a more extended joint (less joint ROM)

The third aim of this study was to identify, using the proposed pathway (steps 1-3), which of the examined exercises (drop jump, jump squat, squat or power clean) was likely to be the most effective at improving the group's or a given individual's CMJ jump height. To this end the proposed pathway was applied using a group and single-subject analysis, respectively. The results of the group level analysis will be presented first followed by the results of the individual level analysis.

The first step in the proposed biomechanical pathway (Figure 2.9, pg77) involved identifying the group's CMJ PRFs. Eight CMJ parameters were found to be significantly ($p<0.01$) correlated with CMJ jump height and were therefore deemed CMJ PRFs (Table 3.12).

Table 3.12 The group's CMJ PRFs

CMJ PRFs	Correlation with CMJ jump height r (p value)	
1. Whole body concentric peak power	0.88*	(<0.001)
2. Whole body concentric work done	0.67*	(<0.001)
3. Ankle concentric peak power	0.62*	(0.001)
4. Time between peak power and takeoff **	-0.56*	(0.003)
5. Hip concentric peak power	0.55*	(0.003)
6. Knee concentric work done	0.54*	(0.004)
7. Amplitude of the centre of mass	0.53*	(0.009)
8. Knee concentric peak power	0.49*	(0.005)

* Significant correlation ($p<0.01$)

** CMJ PRF negatively correlated with jump height means a smaller magnitude was associated with larger jump heights

The acute training stress experienced by each CMJ PRF in each training exercise is identified in Table 3.13 (step 2, Figure 2.9). Based on this information it was possible to identify the expected magnitude change that each CMJ PRF would experience following training with a given training exercise (also presented in Table 3.13) [step 3, Figure 2.9]. This step (step 3) in the proposed pathway is based on the theory of training overload, which states that in order for a component of the neuromuscular system to be enhanced following training it must be stressed at a level beyond which it is accustomed (Zatsiorsky and Kraemer 2006).

Only one CMJ PRF, knee concentric work done, experienced an appropriate training stress in the squat (Table 3.13). Based on this finding an appropriate period of squat training would only be expected to enhance one of the group's seven CMJ PRFs. Similarly, only one CMJ PRF, hip concentric peak power, experienced an appropriate training stress in the power clean (Table 3.13). In light of this an appropriate period of power clean training would also only be expected to enhance one of the group's CMJ PRFs.

Both the drop jump and the jump squat appropriately stressed three CMJ PRFs each (Table 3.13). Whole body, knee and ankle concentric peak power were appropriately stressed in the drop jump while whole body concentric work done, knee concentric work done and ankle concentric peak power were appropriately stressed in the jump squat. It is noteworthy that the drop jump appropriately stressed whole body concentric peak power while the jump squat did not. Whole body concentric peak power had by far the strongest relationship with CMJ jump height (r = 0.88) and thus a change in this parameter would be expected to wield the greatest influence over CMJ jump height. Both the jump squat and drop jump also imposed an inappropriate training stress on two CMJ PRFs: amplitude of the centre of mass and the time between peak power and takeoff (Table 3.13). In light of all of this a period of either drop jump or jump squat training would be expected to enhance three of the group's CMJ PRFs but induce a decline in another two CMJ PRFs (Table 3.13).

Table 3.13 The acute training stress experienced by the group's CMJ PRFs in each training exercise

CMJ PRFs	**Drop Jump**		**Jump Squat**		**Squat**		**Power Clean**	
	Training Stress (percentage difference)	Expected training effect	Training Stress (percentage difference)	Expected training effect	Training Stress (percentage difference)	Expected training effect	Training Stress (percentage difference)	Expected training effect
Whole body concentric peak power	Appropriate stress (12%) *	Enhance	No stress (-13%) *	No change	No stress (-37%) *	No change	No stress (-58%) *	No change
Whole body concentric work done	No stress (-17%) *	No change	Appropriate stress (8%) *	Enhance	No stress (-2%)	No change	No stress (-18%) *	No change
Ankle concentric peak power	Appropriate stress (13%) *	Enhance	Appropriate stress (6%) *	Enhance	No stress (-91%) *	No change	No stress (-55%) *	No change
Time between peak power and takeoff	Inappropriate stress (5%) *	Decline	Inappropriate stress (16%) * [1]	Decline	NA	NA	NA	NA
Hip concentric peak power	No stress (-10%)	No change	No stress (-17%) *	No change	No stress (-59%) *	No change	Appropriate stress (15%) *	Enhance

* Significant difference CMJ versus training exercise (p<0.05)

Red: PRF negatively correlated with jump height - a smaller magnitude is associated with larger jump heights

[1] Inappropriate stress jump squat > inappropriate stress drop jump (p<0.05)

Table 3.13 continued overleaf

Table 3.13 (Continued) The acute training stress experienced by the group's CMJ PRFs in each training exercise

CMJ PRFs	Drop Jump Training Stress (percentage difference)	Drop Jump Expected training effect	Jump Squat Training Stress (percentage difference)	Jump Squat Expected training effect	Squat Training Stress (percentage difference)	Squat Expected training effect	Power Clean Training Stress (percentage difference)	Power Clean Expected training effect
Knee concentric work done	No stress (7%)	No change	Appropriate stress (12%) *	Enhance	Appropriate stress (23%) * [2]	Enhance	No stress (-91%) *	No change
Knee concentric peak power	Appropriate stress (22%) *	Enhance	No stress (-13%) *	No change	No stress (-75%) *	No change	No stress (-85%) *	No change
Amplitude of the COM	Inappropriate stress (-30%) * [3]	Decline	Inappropriate stress (-13%) *	Decline	No stress (-3%)	No change	No stress (-33%) *	No change

* Significant difference CMJ versus training exercise ($p<0.05$)

[2] Appropriate stress squat > appropriate stress jump squat ($p<0.05$)

[3] Inappropriate stress drop jump > inappropriate stress jump squat ($p<0.05$)

Aim three of this study also examined whether applying steps 1-3 of the proposed pathway (Figure 2.9) at the individual subject level could identify the training exercise likely to be most effective at enhancing a given individual's CMJ jump height. It was deemed unnecessary to present the individual level results for each of the twenty-six subjects involved in this study. Instead the results of four subjects (subject 1-4) are presented (Tables 3.14-3.17). These individuals were selected for presentation as their respective results clearly and succinctly demonstrate that (a) the proposed pathway appears to be able to identify the training exercise likely to be most effective at enhancing a given individual's CMJ jump height and, (b) the training exercise deemed most likely to enhance a given individual's CMJ jump height can in fact differ from one individual to another.

Table 3.14 Individual 1's CMJ PRFs and the acute training stress they experienced in the different training exercises

		Drop Jump		Jump Squat		Squat		Power Clean	
CMJ PRFs	r	Training Stress (percentage difference)	Expected training effect	Training Stress (percentage difference)	Expected training effect	Training Stress (percentage difference)	Expected training effect	Training Stress (percentage difference)	Expected training effect
Hip concentric peak power	0.76	No stress (-9%)	No change	No stress (-12%)	No change	No stress (-46%) *	No change	No stress (-7%)	No change
Ratio of early hip concentric work done to late hip eccentric work done	-0.75	Appropriate stress[1] (-156%) *	Enhance	Appropriate stress (-28%) *	Enhance	Appropriate stress (-31%) *	Enhance	NA	NA
Whole body concentric peak power	0.69	Appropriate stress (15%) *	Enhance	No stress (-12%)	No change	No stress (-32%) *	No change	No stress (-47%) *	No change
Whole body eccentric peak vertical velocity	0.68	Appropriate stress (53%) *	Enhance	No stress (-13%)	No change	No stress (-52%) *	No change	NA	NA
Whole body eccentric impulse	0.66	No stress (49%)	No change	No stress (90%) *	No change	Appropriate stress (1107%) *	Enhance	NA	NA

* Significant difference CMJ versus training exercise ($p<0.05$)

Red: PRF negatively correlated with jump height - a smaller magnitude is associated with larger jump heights

[1] Appropriate stress drop jump > appropriate stress jump squat and squat ($p<0.05$)

Table 3.14 continued overleaf

Table 3.14 (Continued) Individual 1's CMJ PRFs and the acute training stress they experienced in the different training exercises

		Drop Jump		**Jump Squat**		**Squat**		**Power Clean**	
CMJ PRFs	r	Training Stress (percentage difference)	Expected training effect	Training Stress (percentage difference)	Expected training effect	Training Stress (percentage difference)	Expected training effect	Training Stress (percentage difference)	Expected training effect
Hip concentric peak moment	0.65	No stress (-3%)	No change	Appropriate stress (13%) *	Enhance	Appropriate stress [2] (28%) *	Enhance	Appropriate stress (18%) *	Enhance
Whole body concentric peak force	0.64	Appropriate stress [3] (47%) *	Enhance	No stress (18%)	No change	Appropriate stress (33%) *	Enhance	No stress (15%)	No change
Whole body concentric work done	0.63	No stress (-36%) *	No change	Appropriate stress (36%) *	Enhance	Appropriate stress (32%) *	Enhance	No stress (-44%) *	No change
Whole body eccentric peak power	0.63	Appropriate stress (85%) *	Enhance	No stress (5%)	No change	No stress (-17%)	No change	NA	NA
Knee concentric peak power	0.61	Appropriate stress (29%) *	Enhance	No stress (-6%)	No change	No stress (-71%) *	No change	No stress (-60%) *	No change

* Significant difference CMJ versus training exercise ($p<0.05$)

Red: PRF negatively correlated with jump height - a smaller magnitude is associated with larger jump heights

[2] Appropriate stress squat > appropriate stress jump squat ($p<0.05$)

[3] Appropriate stress drop jump > appropriate stress squat ($p<0.05$)

Table 3.15 Individual 2's CMJ PRFs and the acute training stress they experienced in the different training exercises

		Drop Jump		Jump Squat		Squat		Power Clean	
CMJ PRFs	r	Training Stress (percentage difference)	Expected training effect	Training Stress (percentage difference)	Expected training effect	Training Stress (percentage difference)	Expected training effect	Training Stress (percentage difference)	Expected training effect
Hip concentric peak moment	0.71	No stress (-27%) *	No change	Appropriate (28%) *	Enhance	Appropriate [1] (65%) *	Enhance	Appropriate [1] (81%) *	Enhance
Hip eccentric work done	0.62	No stress (-77%) *	No change	Appropriate (33%) *	Enhance	Appropriate [2] (291%) *	Enhance	NA	NA
Hip rate of power development at the start of the concentric phase	0.61	No stress (-50%) *	No change	No stress (-45%) *	No change	No stress (-88%) *	No change	Appropriate (196%) *	Enhance
Ankle eccentric peak power	0.56	Appropriate [3] (324%) *	Enhance	Appropriate (46%) *	Enhance	No stress (-4%)	No change	NA	NA
Hip moment at joint reversal	0.56	No stress (-11%) *	No change	Appropriate (33%) *	Enhance	Appropriate [2] (75%) *	Enhance	NA	NA

* Significant difference CMJ versus training exercise ($p<0.05$)

[1] Appropriate stress power clean > appropriate stress squat > appropriate stress jump squat ($p<0.05$)

[2] Appropriate stress squat > appropriate stress jump squat ($p<0.05$)

[3] Appropriate stress drop jump > appropriate stress jump squat ($p<0.05$)

Table 3.16 Individual 3's CMJ PRFs and the acute training stress they experienced in the different training exercises

		Drop Jump		**Jump Squat**		**Squat**		**Power Clean**	
CMJ PRFs	r	Training Stress (percentage difference)	Expected training effect	Training Stress (percentage difference)	Expected training effect	Training Stress (percentage difference)	Expected training effect	Training Stress (percentage difference)	Expected training effect
Whole body concentric work done	0.70	No stress (-5%)	No change	Appropriate (15%) *	Enhance	Appropriate[1] (30%) *	Enhance	No stress (-31%) *	No change
Ankle concentric work done	0.60	No stress (4%)	No change	Appropriate (25%) *	Enhance	No stress (-43%) *	No change	No stress (-77%) *	No change
Knee angle at joint reversal †	-0.59	Appropriate (-6%) *	Decline	No stress (-2%)	No change	Appropriate [2] (-14%)	Enhance	NA	NA
Hip concentric work done	0.55	No stress (-32%) *	No change	No stress (5%)	No change	Appropriate [3] (74%)	Enhance	Appropriate (23%)	Enhance

* Significant difference CMJ versus training exercise ($p<0.05$)

Red: PRF negatively correlated with jump height - a smaller magnitude is associated with larger jump heights

† A more flexed knee at joint reversal (indicating a greater ROM) is associated with larger jump heights

[1] Appropriate stress squat > appropriate stress jump squat ($p<0.05$)

[2] Appropriate stress squat > appropriate stress drop jump ($p<0.05$)

[3] Appropriate stress squat > appropriate stress power clean ($p<0.05$)

Table 3.17 Individual 4's CMJ PRFs and the acute training stress they experienced in the different training exercises

CMJ PRFs	r	Drop Jump		Jump Squat		Squat		Power Clean	
		Training Stress (percentage difference)	Expected training effect	Training Stress (percentage difference)	Expected training effect	Training Stress (percentage difference)	Expected training effect	Training Stress (percentage difference)	Expected training effect
Whole body concentric peak power	0.74	No stress (4%)	No change	No stress (-9%) *	No change	No stress (-42%) *	No change	No stress (-74%) *	No change
Whole body concentric work done	0.61	No stress (-20%)	No change	No stress (10%)	No change	No stress (2%)	No change	No stress (-12%)	No change
Time between peak power and takeoff	-0.58	Inappropriate (14%) *	Decline	No stress (5%)	No change	NA	NA	NA	NA
Hip concentric work done	0.56	No stress (-54%) *	No change	No stress (5%)	No change	No stress (23%)	No change	Appropriate (49%) *	Enhance
Hip concentric peak moment	0.53	No stress (16%)	No change	Appropriate (21%) *	Enhance	Appropriate [1] (35%) *	Enhance	Appropriate [1] (60%) *	Enhance

* Significant difference CMJ versus training exercise (p<0.05)

[1] Appropriate stress power clean > appropriate stress squat > appropriate stress jump squat (p<0.05)

The fourth and final aim of this study was to examine whether a subgroup (or subgroups) of individuals could be identified for whom the training exercise selected as being the most effective for the group may not be the most effective to enhance their CMJ jump height. To this end subjects were subgrouped based on the magnitude of pre-training stress experienced by the CMJ PRFs (which were identified in the group analysis) in the drop jump.

Five CMJ parameters were used in the cluster analysis (Table 3.18). Hip concentric peak power and amplitude of the centre of mass were excluded from the analysis as they were both highly correlated with whole body concentric work done (r = 0.78 and 0.89, respectively). Similarly, knee concentric peak power was excluded from the analysis as it was highly correlated with knee concentric work done (r = 0.77) [see section 3.2.6 for more details].

Table 3.18 CMJ parameters used in the cluster analysis

1. Whole body concentric peak power
2. Whole body concentric work done
3. Ankle concentric peak power
4. Time between peak power and takeoff
5. Knee concentric work done

A relatively large increase in the agglomeration coefficient occurred between the four subgroup and three subgroup solutions (27% increase) [Table 3.19], indicating that a four subgroup solution was appropriate. The dendrogram produced by the cluster analysis is provided in Figure 3.4. Solution validity was examined by checking for between subgroup differences in the magnitude of pre-training stress which was confirmed with a significant MANOVA Wilks' γ = 0.02, $p<0.001$. The various between subgroup differences in magnitude of pre-training stress experienced by the CMJ PRFs are outlined in Table 3.20 (bottom row). The actual pre-training stress experienced by each CMJ PRF for each subgroup (i.e. appropriate, inappropriate or no training stress) is also provided, as is a reminder of the pre-training stress experienced at the group level.

Table 3.19 Change in the agglomeration coefficient as the number of subgroups changed

Change in number of subgroups	Agglomeration coefficient	Percentage change in agglomeration coefficient
7 to 6	32.4	20
6 to 5	39.3	21
5 to 4	46.2	18
4 to 3	58.9	27
3 to 2	81	38
2 to 1	125	54

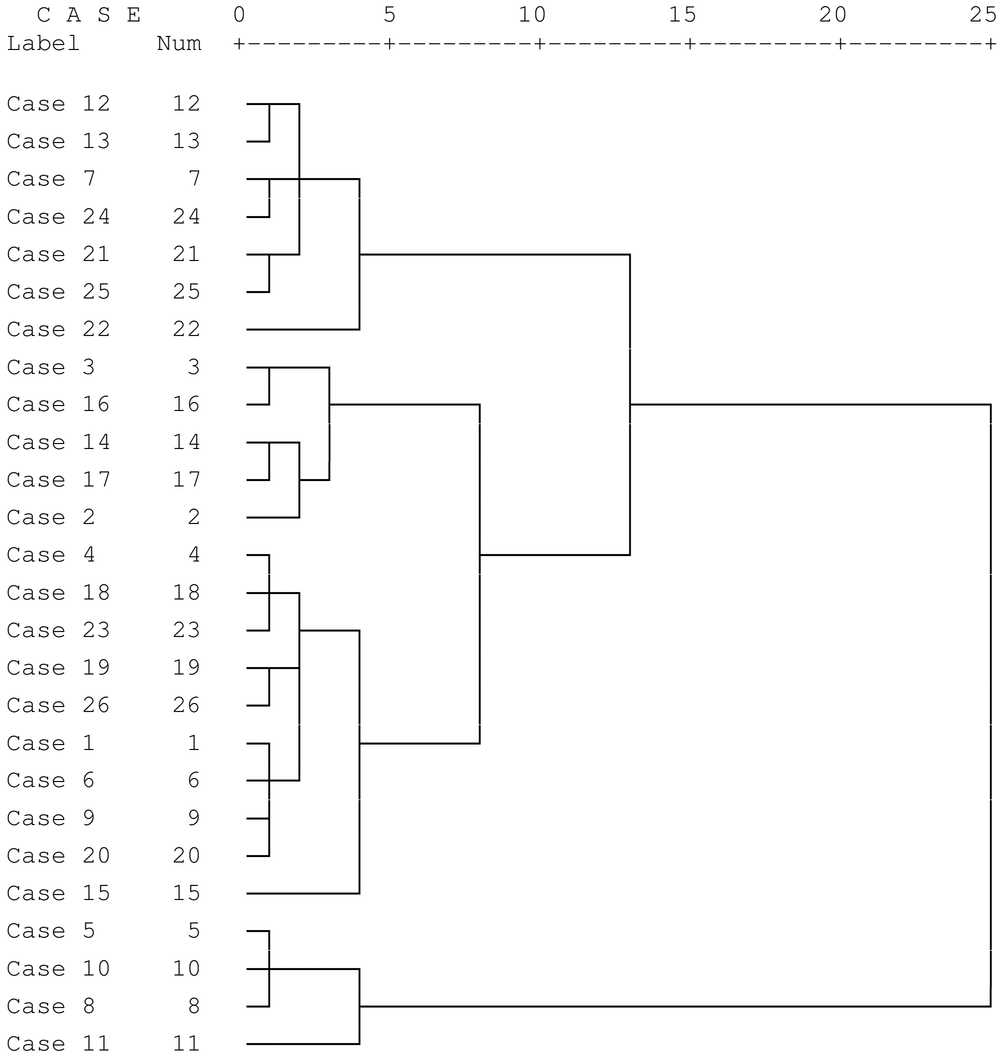

Figure 3.4 Dendrogram produced in the Ward's method hierarchal cluster analysis

Table 3.20 The magnitude of training stress (DJ-CMJ) experienced by each subgroup in the DJ

	WB concentric peak power (W.kg^{-1})	WB concentric work done (J.kg^{-1})	Ankle concentric peak power (W.kg^{-1})	Time between peak power and takeoff (ms)	Knee concentric work done (J.kg^{-1})
Main group (n=26)	5.9 ± 6.6 Appropriate stress *	-1.3 ± 0.9 No stress *	3.7 ± 6.5 Appropriate stress *	3.2 ± 2.9 Inappropriate stress *	0.1 ± 0.2 No stress
Subgroup 1 (n = 10)	0.5 ± 1.5 No stress	-1.1 ± 0.8 No stress *	-0.4 ± 1.9 No stress	2.5 ± 2.1 Inappropriate stress *	0.0 ± 0.1 No stress
Subgroup 2 (n = 5)	7.8 ± 4.0 Appropriate stress *	-2.3 ± 0.8 No stress *	5.1 ± 3.2 Appropriate stress *	3.5 ± 2.0 Inappropriate stress *	0.1 ± 0.1 No stress
Subgroup 3 (n = 4)	17.9 ± 4.5 Appropriate stress *	-2.0 ± 0.6 No stress *	16.5 ± 5.4 Appropriate stress *	-0.3 ± 1.2 No stress	0.1 ± 0.2 No stress
Subgroup 4 (n = 7)	5.2 ± 2.8 Appropriate stress *	-0.6 ± 0.5 No stress *	1.3 ± 2.6 No stress	6.1 ± 2.4 Inappropriate stress *	0.4 ± 0.2 Appropriate stress *
Between subgroup differences ($p < 0.05$)	3>2,4>1	2>1,4 3>4	3>2>1 3>4	4>1,3	4>1,2,3

* Significant difference DJ magnitude vs. CMJ magnitude ($p<0.05$)

Red: PRF negatively correlated with jump height means a smaller magnitude is associated with larger jump height

Based on the data provided in Table 3.20, the CMJ PRF post-training changes that each subgroup would be expected to experience following drop jump training are outlined in Table 3.21.

Table 3.21 The expected CMJ PRF post-training change that each subgroup would experience following DJ training

	WB concentric peak power	WB concentric work done	Ankle concentric peak power	Time between peak power and takeoff	Knee concentric work done
Main group (n=26)	Enhance	No change	Enhance	Decline	No change
Subgroup 1	No change	No change	No change	Decline	No change
Subgroup 2	Enhance	No change	Enhance	Decline	No change
Subgroup 3	Enhance [1]	No change	Enhance [1]	No change	No change
Subgroup 4	Enhance	No change	No change	Decline [2]	Enhance

[1] Subgroup 3 enhancement > Subgroup 2 enhancement

[2] Subgroup 4 decline > subgroup 1 decline

3.4 Discussion

CMJ performance related factors (PRFs) are those CMJ kinetic and kinematic parameters that are significantly related to CMJ jump height. Researchers typically identify CMJ PRFs based on the assumption that they (CMJ PRFs) are likely to be true CMJ performance determining factors (CMJ PDFs) [see section 2.2.2 for more details]. The first aim of this study was to examine whether CMJ PRFs are consistent across individuals or whether different individuals have the capacity to possess a unique set of CMJ PRFs. The results of this study clearly show that different individuals have the potential to have a unique set of CMJ PRFs as exemplified by the results of the five representative individuals presented in Tables 3.5-3.9. For example, two of the three CMJ PRFs identified for individual E, whole body RPD at the start of the concentric phase and knee eccentric work done, were not identified as CMJ PRFs for any of the other individuals presented. Further evidence that different individuals have the capacity to possess unique CMJ PRFs was provided in Table 3.10. Despite the fact that the eight parameters detailed in Table 3.10 were group level CMJ PRFs there was much between subject variability in whether or not these parameters were CMJ PRFs at the individual subject level. For example, even though whole body peak power had the strongest correlation with jump height at the group level, only seven of the twenty-six subjects had this parameter as a CMJ PRF, while the remaining nineteen subjects did not (Table 3.10).

Similar to the current study, Aragon-Vargas and Gross (1997a) also found that different individuals have the potential to have different CMJ PRFs. For example, amplitude of the body's centre of mass was the best single predictor of CMJ jump height ($r = 0.56$) for individual A (pp54) but contrastingly was not a notable predictor of jump height for individual B (pp55). If CMJ PRFs can be considered to be true CMJ PDFs, the findings of both the current study and that of Aragon-Vargas and Gross (1997a) would suggest that different individuals have the capacity to possess different CMJ PDFs. This is in accordance with the theory that individuals may have a unique neuromuscular solution for a given task (Bates 1996). Possible sources of individual uniqueness include inter-individual differences in neuromuscular capacity (e.g. joint power, joint dominance), anthropometrics (e.g. limb lengths), muscle morphology (e.g. percentage muscle fiber type), personal technique preference and past-training experience.

The second aim of this study was to examine whether the acute training stress experienced by CMJ kinetic and kinematic parameters in a given exercise is consistent across individuals or whether it may be subject to inter-individual variation. The current study found that the extent to which a kinetic or kinematic parameter's magnitude was significantly different (or not different) in a training exercise compared to the CMJ was often subject to inter-individual variation. In other words, a capacity for inter-individual variability in the acute training stress experienced by a given CMJ parameter, in a given training exercise (drop jump, jump squat, squat or power clean), was observed. For example, ankle concentric peak moment was found to be significantly greater in the jump squat than the CMJ for fourteen individuals (Table 3.11). This suggests that ankle peak moment experienced an acute training stress in the jump squat for these individuals and would thus be expected to enhance following a suitable training period. In contrast, the same CMJ parameter experienced no training stress for another twelve individuals and would thus not be expected to experience any post-training magnitude change. These findings imply that even when individuals train with the same training exercise, exercise intensity and duration, they may experience different CMJ parameter magnitude changes following training.

Previous studies have also provided evidence of inter-individual variability in the acute training stress experienced during a training exercise. Bobbert et al. (1986a) noticed that when subjects were asked to drop jump (from 40cm) there appeared to be a jump technique continuum between fast, small amplitude drop jumps (bounce drop jumps), and slow, large amplitude drop jumps (counter drop jumps). The authors realised that these inter-individual differences led to inter-individual differences in the stress imposed by the drop jump. For example, knee concentric peak moment and peak power were significantly greater (by 52% and 31%, respectively) in the bounce drop jump group in comparison to the CMJ, while these parameters were not different in the counter drop jump group in comparison to the CMJ. Similarly, Fry et al. (2003) found that the peak concentric knee moments produced during a squat showed much inter-individual variation depending on the squatting technique employed. Squats with greater anterior knee displacement produced significantly greater knee moments (28% greater) than squats with a more restricted knee anterior displacement.

In light of the results discussed above (aims one and two), it can be argued that the inconsistent outcomes of respective training exercise interventions aimed at enhancing CMJ jump height (see Tables 2.24, 2.30, 2.32 and 2.35) may be in part due to: (a) different individuals possessing different CMJ PDFs, and\or (b) different individuals experiencing different training stresses in a given training exercise. It is apparent therefore that any methods developed to improve current exercise prescription practises should take both ‘a’ and ‘b’ into account. One such method, a biomechanical diagnostic and prescriptive pathway, (Figure 2.9) has been proposed. The proposed pathway may be applied to help identify the exercise most likely to enhance a given group’s, subgroup’s or individual’s CMJ jump height.

The third aim of the current study was, in part, to utilise the proposed pathway (steps 1-3) to identify which of the following training exercises was likely to be the most effective at improving the group’s mean CMJ jump height: drop jump, jump squat, squat or power clean. The first step in applying the proposed biomechanical pathway at the group level was to identify the group’s CMJ PRFs. Eight CMJ PRFs were identified (Table 3.12) with whole body concentric peak power exhibiting the strongest relationship with CMJ jump height (r = 0.88). Dowling and Vamos (1993), Aragon-Vargas and Gross (1997b) and Harman et al. (1990) also found a significant and strong correlation between peak power and CMJ jump height (r = 0.93, 0.72 and 0.86, respectively). Given the large correlation between whole body peak power and jump height it is not surprising that peak concentric powers at the hip, knee and ankle joints were also identified as CMJ PRFs (r = 0.55, 0.49 and 0.62, respectively). In contrast to the current study, Vanrenterghem et al. (2008) found neither peak ankle power (r = 0.18) nor peak knee power (r = -0.12) to be correlated with jump height. These contrasting findings may be due to the fact that different individuals (and thus groups) can have different CMJ PRFs (as discussed above). This highlights the need to identify each distinct group's CMJ PRFs when applying the proposed biomechanical pathway at the group level. Of the four remaining CMJ PRFs identified in the current study, both the amplitude of the body's centre of mass (r = 0.53) and the time between peak power and takeoff (r = -0.56) were identified as CMJ PRFs in previous studies (Harman et al. 1990; Aragon-Vargas and Gross 1997b) while whole body and knee concentric work done (r = 0.67 and r = 0.54, respectively) do not appear to have been previously investigated as potential CMJ PRFs.

It is noticeable that no eccentric parameters were identified as group level CMJ PRFs in the current study (Table 3.12). This may seem surprising given that the eccentric loading phase influences concentric phase kinetic outputs (Bobbert et al. 1996; Bosco et al. 1981), which in turn determine CMJ jump height. However, it is possible that many eccentric parameters have an optimal parameter magnitude beyond which further increases in magnitude do not lead to concomitant increases in concentric neuromuscular output (and jump height). For example, Takarada et al. (1997) found that concentric peak power output in a squat increased significantly (~25%) with initial increases in eccentric force (~35%) but larger increases in eccentric force (~50%) did not lead to larger peak power outputs, in fact, peak power output declined. While eccentric based parameters were not identified as CMJ PRFs at the group level this does not imply that they were not identified as CMJ PRFs at the individual subject level. Indeed eccentric parameters were deemed to be CMJ PRFs for a number of individuals (Tables 3.14-3.17).

It is also noticeable that no coordination parameters were identified as CMJ PRFs in the group level analysis (Table 3.12). This is perhaps again surprising given the reported importance of coordination to CMJ performance (see sections 2.2.10 and

2.2.11 for more details). Bobbert and van Soest (1994) theorise that jumping achievement depends largely on the precise timing of muscle actions but that optimal timing may vary from individual to individual depending on the strength of the different muscle groups involved. Group level analysis may not be sensitive to such inter-subject variability and this may explain the absence of coordination based CMJ PRFs at a group level.

The next step in applying the proposed biomechanical pathway at the group level was to identify the acute-training stress CMJ PRFs experienced in the drop jump, jump squat, squat and power clean.

Hip concentric peak power was the only group level CMJ PRF appropriately stressed in the power clean while the remaining seven CMJ PRFs experienced no pre-training stress (Table 3.13). Most notably, despite Kawamori and Haff's (2004) claim that the power clean has the ability to facilitate a large whole body power output, the power clean was found to produce the lowest whole body peak power output of all the exercises examined (Table 3.13).

Only one CMJ PRF, knee concentric work done, experienced an appropriate training stress in the squat. In light of the low velocity of movement in the squat, and the fact that power is the product of force and velocity, it is perhaps not surprising to find that both whole body and joint peak powers were not appropriately stressed (Table 3.13). Given the large forces associated with squatting (see section 2.3.4.1) it may seem surprising that whole body concentric work done was not greater in the squat than the CMJ. This finding may be explained by the fact that the ankle joint does not fully extend in the squat (heels stay on the floor) and thus cannot contribute as much to whole body work done as in the CMJ. Indeed ankle concentric work done was 1.4 times greater ($p<0.05$) in the CMJ than in the squat.

Three CMJ PRFs experienced an appropriate pre-training stress in the jump squat: whole body concentric work done, ankle concentric peak power and knee concentric work done (Table 3.13). It is interesting to observe that the jump squat overcame the limitation outlined above for the squat in that it utilised a greater ankle range of motion, which allowed for a greater amount of whole body work to be done in comparison to the CMJ. Whole body concentric peak power or hip and knee concentric peak power were not appropriately stressed in the jump squat (Table 3.13). Cormie et al. (2008) similarly found that whole body peak power was not greater in loaded jump squats (20kg-80kg) in comparison to the CMJ. Collectively these findings refute the popularly held belief that loaded jump squats maximise whole body concentric peak power production (Crewther et al. 2005). In addition, two technique based CMJ PRFs, amplitude of the body's COM and the time between peak power and takeoff, experienced an inappropriate training stress in the jump squat.

Similar to the jump squat, three CMJ PRFs experienced an appropriate training stress in the drop jump: whole body, ankle and knee concentric peak power (Table 3.13). Bobbert et al. (1987a) also found that peak powers at the knee and ankle were significantly greater (by 7% and 82% respectively) in the drop jump (bounce type) compared to the CMJ. The drop jump utilised in the current study could be broadly categorised as a bounce style drop jump as the group mean concentric phase duration (196ms) met the criteria proposed by Bobbert et al. (1986a) (<200ms) for a bounce drop jump. Of interest, both the current study and Bobbert et al. (1987a) found that hip concentric peak power was not appropriately stressed in the drop jump suggesting that the drop jump, as used in the present study, might neglect to train the hip extensor muscles during the concentric phase (Holcomb et al. 1996b), or at least not train the hip to the same extent as the ankle and knee. Neither whole body concentric work done nor knee concentric work done experienced an acute training stress in the drop jump (Table 3.13). This was presumably due to the significantly ($p<0.05$) smaller amplitude of movement (Table 3.13) and knee range of motion (7.5° more extended knee angle at joint reversal) in the drop jump in comparison the CMJ. Similar to the jump squat, the amplitude of the body's COM and the time between peak power and takeoff experienced an inappropriate training stress in the drop jump (Table 3.13).

Step three of the proposed pathway (Figure 2.9) involves using the information gathered in step two to identify the expected post-training changes that CMJ PRFs may experience following training with each of the respective training exercises. A suitable period of either squat (80% 1RM) or power clean (75% 1RM) training would only be expected to enhance one of the group's CMJ PRFs (Table 3.13) while a suitable period of either drop jump (30cm) or jump squat (30% 1RM) training would be expected to enhance three of the group's CMJ PRFs (Table 3.13). Of note the drop jump appropriately stressed whole body concentric peak power while the jump squat did not. Whole body concentric peak power had by far the strongest relationship with CMJ jump height (r = 0.88) and thus a post-training change in this parameter would be expected to wield the greatest influence over CMJ jump height change. A period of drop jump and jump squat training would also however be expected to lead to post-training declines in the amplitude of the body's COM and the time between peak power and takeoff (Table 3.13). This is based on the assumption that an extended period of training with a given training exercise can lead to changes in CMJ coordination and technique and that these changes may not necessarily be beneficial to performance outcome (see section 2.3.1 for more details). It is possible however, that these post-training declines may be prevented if the group were to undertake CMJ repetitions throughout either their drop jump or jump squat training periods. This is based on the theory proposed by Bobbert et al. (1987a) that incorporating CMJ repetitions into a drop jump training period may prevent 'unlearning' the proper CMJ coordination (Bobbert et al. 1987a).

Step four of the proposed pathway (Figure 2.9) involves using the information gathered in step three to identify the training exercise that is likely to be most effective at enhancing the group's CMJ PRFs, and thus CMJ jump height. Of the four exercises examined the drop jump would be expected to be the most effective at enhancing the group's mean CMJ jump height. This is based on the premise that a suitable period of drop jump training would be expected to enhance three CMJ PRFs, including the most important CMJ PRF whole body peak power, and that the potential declines in two CMJ PRFs could be prevented with the addition of CMJ repetitions throughout the training period.

Aim three of this study also involved utilising the proposed pathway (steps 1-3) to identify which of the following training exercises was likely to be the most effective at improving a given individual's CMJ jump height: drop jump, jump squat, squat or power clean. The results of the current study showed that by applying the proposed pathway at an individual subject level it was possible to identify the training exercise that may be most effective at improving a particular individual's CMJ jump height. Of the four training exercises investigated, the drop jump would be expected to be the most effective at enhancing individual 1's CMJ jump height. This is based on the observation that the drop jump appropriately stressed more of this individual's CMJ PRFs than any other exercise (Table 3.14). Using the same logic, the jump squat would be considered most effective for individual 2 (Table 3.15), the squat for individual 3 (Table 3.16) and the power clean for individual 4 (Table 3.17). The finding that one particular training exercise may be more suited than another at increasing a given individual's CMJ jump height is not surprising given that the current study has already shown that different individuals have the capacity to have different CMJ PRFs, and experience different training stresses in a given training exercise (aims one and two respectively).As such, these findings support the application of the proposed pathway at an individual level in order to identify the most appropriate exercise for each unique individual.

As outlined in section 2.4.2, some limitations inherent with single-subject analysis may undermine the application of the proposed pathway at an individual subject level. It may therefore be worth applying the proposed pathway using a combination of both a group and subgroup (cluster) analysis. That is, use the group analysis to identify the training exercise most likely to enhance the group's jump height and then apply a cluster analysis to examine whether subgroups of individuals exist for whom this training exercise may not be most suitable. A more suitable training exercise could then be found for these subgroups by reapplying the pathway using a group analysis. Such a mixed methods approach may increase the likelihood of prescribing the most effective exercise to the majority of individuals, while avoiding the potential limitations of a single-subject analysis.

The fourth and final aim of the current study examined whether a subgroup (or subgroups) of individuals could be identified for whom the training exercise selected as being the most effective for the group, may not be the most effective to enhance that subgroup's CMJ jump height. While the drop jump was considered the most appropriate training exercise to prescribe to increase the group's mean CMJ jump height, the cluster analysis identified one subgroup of individuals (subgroup one) for whom the drop jump would not be considered an appropriate exercise (Table 3.21). This is based on the observation that none of subgroup one's CMJ PRFs experienced an appropriate training stress in the drop jump. In order to identify a more appropriate exercise for subgroup one the proposed pathway could be applied to this subgroup using a group analysis (as described in section 3.2.6). The findings of the current study thus suggest that by applying the proposed pathway using both a group and subgroup (cluster) analysis it may be possible to increase the likelihood of prescribing the most effective exercise to the majority of individuals, while avoiding the potential limitations of a single-subject analysis.

While the findings of aim three and four suggest that the proposed pathway (Figure 2.9) may provide a means by which to identify the most effective exercise for a given group, subgroup and individual, this is clearly based on the findings (statistical relationships and differences) of an acute study. Statistical findings from such acute studies require confirmation with intervention based study designs.

3.5 Conclusion

The present study provided evidence to suggest that: (a) different individuals may have the capacity to possess their own unique CMJ PDFs and (b) different individuals have the ability to experience different acute training stresses in a given training exercise. Collectively, these findings may, in part, explain why the effects of respective training exercises aimed at improving CMJ jump height are often inconsistent. In light of all of this it is appropriate that the proposed biomechanical diagnostic and prescriptive pathway takes into account that different individuals (and thus groups) may possess different CMJ PDFs, and may experience different training stresses in a given training exercise. This study also demonstrated that the proposed biomechanical diagnostic and prescriptive pathway could identify the training exercise (from the squat, drop jump, jump squat and power clean) that may be most likely to enhance a given group's and individual's CMJ jump height. Finally, by applying the proposed pathway using both a group and subgroup (cluster) analysis it appears possible to increase the likelihood of prescribing the most effective exercise (from the squat, drop jump, jump squat and power clean) to the majority of individuals, while avoiding any potential limitations of a single-subject analysis.

Chapter 4

Study 2: Can a pre-training stress analysis provide an insight into the training effect that eight weeks of drop jump training will have on countermovement jump height?

4.1 Introduction

The results of training studies that have examined the respective effects of drop jump, squat, jump squat and power clean training on CMJ jump height are generally inconsistent (section 2.3, Tables 2.24, 2.30, 2.32 and 2.35, respectively). Consequently, coaches cannot be sure as to which training exercise will be most effective at enhancing their athletes' CMJ jump height. Clearly this is an unsatisfactory situation, especially when working with elite athletes. In an attempt to address this issue a biomechanical diagnostic and prescriptive pathway has been proposed (Figure 2.9 pg77, see section 2.4 for a detailed description). The previous study (study 1) demonstrated that the proposed pathway may, in theory, be able to identify the most appropriate training exercise for a given group, subgroup or individual. However, these findings were based on the results of an untested hypothesis that an acute pre-training stress analysis can provide an insight into the training effect that a given exercise will have on CMJ jump height. A pre-training stress analysis involves identifying the training stress experienced by CMJ performance related factors (PRFs)[1] in a given training exercise and using this information to propose the likely effects of that exercise on jump height. In addition, two inherent assumptions of such an analysis, that the pre-training stress experienced by a given CMJ PRF will give an insight into its post-training magnitude change and that CMJ PRFs are likely to be true CMJ performance determining factors (PDFs) [see section 2.2.2 for the distinction between PRFs and PDFs], remain untested. The current study therefore aimed to examine these

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[1] While CMJ PDFs are those CMJ parameters that ultimately determine jump height they cannot be identified experimentally in an acute testing session, as a true cause and effect relationship cannot be established. Instead, CMJ PRFs are identified on the assumption that they are likely to be CMJ PDFs. CMJ PRFs are those CMJ parameters that are significantly correlated with CMJ jump height (see section 2.2.2 for more details).

respective hypotheses with the use of an eight-week drop jump training intervention.

The following aim and sub-aims were investigated at a group, subgroup and individual subject level:

(1) To determine whether an analysis of the acute pre-training stress experienced by CMJ PRFs in the drop jump could provide an insight into the effect that eight weeks of drop jump training will have on CMJ jump height.

Sub-aim 'a': To determine if the acute pre-training training stress experienced by CMJ PRFs in the drop jump could explain the post-training magnitude change in these same CMJ PRFs following eight weeks of training.

Sub-aim 'b': To determine if the post- training magnitude change experienced by CMJ PRFs following eight weeks of drop jump training could explain the post-training change in CMJ jump height.

Hypotheses:

(1) Based on the results of the pre-training stress analysis it will be possible to pre-determine the training effect that drop jump training will have on CMJ jump height.

Sub-hypothesis (a): Based on the acute pre-training stress experienced by CMJ PRFs in the drop jump it will be possible to pre-determine their post-training magnitude change.

Sub-hypothesis (b): The post-training change experienced by CMJ PRFs will ultimately determine the post-training change in CMJ jump height.

4.2 Methodology

4.2.1 Subjects

68 injury free athletic male adults (mean ± *SD*: age, 22 ± 4 years; weight 78.2 ± 9.5 kg) were recruited from students at Dublin City University. All participants were competitively active in a sport that involved a jump and, while all had previously utilised the drop jump (DJ) in previous training routines, none had undertaken structured DJ training in the previous three months. After the nature and risks of the study were explained each participant gave a written informed consent as required by the University Ethics Committee.

4.2.2 Experimental protocol

A biomechanical analysis of each subject's CMJ and DJ (30cm drop height) was carried out both before and after an eight-week period of DJ training. Participants attended a familiarisation session prior to the pre-training testing session in order to familiarise themselves with the testing protocol. Participants were also asked to refrain from any strenuous activity for 48 hours before the laboratory test. A standard warm-up routine, consisting of low intensity jogging, stretching and three sub-maximal trials of both the DJ and CMJ preceded testing. For the actual testing, each subject performed fifteen CMJ trials and five DJ trials. The trials were performed with feet approximately shoulder width apart and with each foot on an independent force platform. Feet were kept parallel with the x-axis of the force platform, restricting motion to the sagittal plane as much as possible. Hands were placed on the hips to prevent the use of the arms (Vanrenterghem et al. 2008). Subjects wore brief shorts and their own athletic shoes. The CMJ and DJ were carried out as previously described (see sections 2.2.1 and 2.3.3). For the CMJ subjects were instructed to countermove to a self-selected depth then jump as high as possible (Bobbert et al. 1987a). For the DJ subjects were instructed to perform a DJ for maximal jump height while attempting to minimise ground contact time (Matavulj et al. 2001). No additional instructions were given to ensure self-selection of technique and minimisation of any investigator-induced bias into the experiment. A drop height of 30cm was chosen for the DJ as such a height is commonly used in training (Young et al. 1999). After completing all fifteen repetitions of the CMJ, subjects rested for three minutes before completing the five DJ repetitions. Adequate rest was permitted between respective CMJ and DJ repetitions (30 seconds).

4.2.3 Data acquisition

The method of CMJ and DJ data acquisition described in section 3.2.3, pg95 (Study 1) was used in this study.

4.2.4 Data analysis

The method of CMJ and DJ data analysis described in section 3.2.4, pg96 (Study 1) was used in this study.

4.2.5 Variables analysed

The kinetic and kinematic variables outlined in section 3.2.5, pg101 (Study 1) were also analysed in this study.

4.2.6 Training Protocol

Participants were randomly assigned to either a DJ training group (n=34) or a control group (n=34). DJ training consisted of four sets of eight DJs, from a 30cm drop height, three times a week for eight weeks. The recovery time between repetitions and sets was fifteen seconds and two minutes, respectively (Potach and Chu 2000; Read and Cisar 2001). Each training session was supervised to ensure all sets and repetitions were completed appropriately. DJ training programs that have used a similar duration and session frequency have resulted in group based improvements in CMJ jump height (Bobbert 1990; Holcomb et al. 1996b). While drop heights in training studies have varied from 25cm to 100cm there is no evidence to suggest that larger drop heights lead to greater improvements in CMJ jump height (Bobbert 1990). In addition, Lees and Fahmi (1994) suggest that if an optimal drop height were to exist it would be at lower rather than greater drop heights. A 30cm drop height was therefore deemed a suitable drop height to employ in this training study. As there is no evidence based research regarding the optimal increments by which to increase drop height over the course of a training period, or indeed when these increments should be introduced, no attempt was made to alter drop heights for any individual over the eight week training period. No control was administered for other physical activities or sporting participation, in either the training or control groups, with the exception that no other lower body plyometric or resistance training exercises were to be performed.

4.2.7 Statistical analysis

Statistical analysis was run at a group, subgroup and individual level as detailed below.

4.2.7.1 Group level

The group's CMJ PRFs (step 1, Figure 2.9), CMJ PRF pre-training stresses (step 2, Figure 2.9) and expected CMJ PRF post-training changes (step 3, Figure 2.9) were all identified using the same statistical analyses and procedures outlined in section 3.2.6 (study 1). The one exception was that dependent t-tests were used to identify pre-training stress in the current study rather than a repeated measures ANOVA; an ANOVA was not necessary as only one training exercise (the DJ) was being analysed.

Additional statistical analyses were required to examine the specific aim and sub-aims of this study. For these analyses the mean data from each individual's best three jumps was used and an $\alpha = 0.05$ was adopted for statistical significance. The post-training changes in jump height and CMJ PRF magnitudes in the training group were assessed using dependent t-tests. In addition, independent t-tests were used to determine if post-training magnitude changes were significantly different when compared to the control group. Aim one of the current study was specifically addressed by examining whether the pre-training stresses experienced by the CMJ PRFs ($DJ_{PRE} - CMJ_{PRE}$) could explain the post-training change in CMJ jump height ($CMJ_{POST} - CMJ_{PRE}$). Sub-aim 'a' was addressed by examining whether the pre-training stress experienced by a CMJ PRF ($DJ_{PRE} - CMJ_{PRE}$) could explain the post-training magnitude change in these same CMJ PRFs ($CMJ_{POST} - CMJ_{PRE}$). In addition, the relationship between the pre-training stress experienced by a given CMJ PRF (DJ_{PRE} – CMJ_{PRE}) and its post-training magnitude change (CMJ_{POST} – CMJ_{PRE}) was investigated using a Pearson product moment correlation. Sub-aim 'b' was specifically addressed by examining whether the cumulative post-training magnitude changes experienced by the CMJ PRFs (CMJ_{POST} – CMJ_{PRE}) could explain the post-training change in CMJ jump height (CMJ_{POST} – CMJ_{PRE}). In addition, the relationship between the post-training magnitude change experienced by each CMJ PRF (CMJ_{POST} – CMJ_{PRE}) and the post-training change in CMJ jump height (CMJ_{POST} – CMJ_{PRE}) was investigated using a Pearson product moment correlation.

4.2.7.2 Subgroup level

At the subgroup level the mean data from each individual's best three jumps was used and an $\alpha = 0.05$ was adopted for statistical significance. Individuals were subgrouped using a Ward's method hierarchical agglomerative cluster analysis, as described in section 3.2.6 (study 1). The magnitude of post-training change experienced by the CMJ jump height and CMJ PRFs (CMJ_{POST} – CMJ_{PRE}) was compared across subgroups (and the control group) using a MANOVA. Where a significant difference was found, a post hoc comparison was undertaken with appropriate Bonferroni adjustment. Within group post-training changes were identified using dependent t-tests.

Aim one of the current study was addressed by examining whether the acute pre-training stress experienced by the CMJ PRFs (DJ_{PRE} – CMJ_{PRE}) in each respective subgroup could explain each subgroup's post-training CMJ jump height change (CMJ_{POST} – CMJ_{PRE}). Sub-aim 'a' was specifically addressed by examining whether the pre-training stress experienced by a given CMJ PRF (DJ_{PRE} – CMJ_{PRE}) could explain the post-training magnitude change in that same CMJ PRF (CMJ_{POST} – CMJ_{PRE}). Sub-aim 'b' was specifically addressed by examining whether the cumulative post-training magnitude changes experienced by the CMJ PRFs (CMJ_{POST} – CMJ_{PRE}) for a particular subgroup could explain that subgroup's post-training change in CMJ jump height (CMJ_{POST} – CMJ_{PRE}).

4.2.7.3 Individual level

Each individual's CMJ PRFs (step 1, Figure 2.9), CMJ PRF pre-training stresses (step 2, Figure 2.9) and expected CMJ PRF post-training changes (step 3, Figure 2.9) were identified using the same statistical analyses and procedures outlined in section 3.2.6 (study 1). The one exception was that independent t-tests were used to identify pre-training stress in this study rather than an independent ANOVA. The post-training change in CMJ jump height and CMJ PRF magnitudes experienced by an individual was assessed using dependent t-tests. All fifteen of an individual's CMJ trials were used in these t-tests and an $\alpha = 0.05$ was adopted for statistical significance.

Aim one of the current study was specifically addressed by examining whether the pre-training stresses experienced by an individual's CMJ PRFs in the DJ ($DJ_{PRE} - CMJ_{PRE}$) could explain that individuals post-training change in CMJ jump height ($CMJ_{POST} - CMJ_{PRE}$). Sub-aim 'a' was addressed by examining whether the pre-training stress experienced by a given CMJ PRF ($DJ_{PRE} - CMJ_{PRE}$) could explain its post-training magnitude change ($CMJ_{POST} - CMJ_{PRE}$). Sub-aim 'b' was addressed by examining whether the cumulative post-training magnitude changes experienced by an individual's CMJ PRFs ($CMJ_{POST} - CMJ_{PRE}$) could explain that individual's post-training change in CMJ jump height ($CMJ_{POST} - CMJ_{PRE}$).

4.3 Results

This section will begin by presenting the post-training CMJ jump height change results for the training group and every individual within the training group. The results of the various analyses undertaken at the group, subgroup and individual level will then be presented (in that order).

4.3.1 CMJ jump height change results

CMJ jump height did not change significantly ($p>0.05$), pre test versus post test, in either the training or the control groups (Table 4.1).

Table 4.1 Group level CMJ jump height changes

	n	Jump height pre (cm)	Jump height post (cm)	Percentage change	p
Training group	34	49.7 ± 4.9	49.5 ± 4.4	-0.4	0.7
Control group	34	47.3 ± 5.8	47.2 ± 5.4	-0.2	0.7

Based on each individual's data it was observed that within the training group nine individuals significantly ($p<0.05$) improved their CMJ jump height, twenty had no significant change and five individual's CMJ jump height significantly reduced (Table 4.2). It is worth noting that the cluster analysis, which subgrouped individuals based on the magnitude of pre-training stress they experienced, did not place individuals in homogenous subgroups in terms of post-training jump height change.

Table 4.2 Individual level CMJ jump height changes

	Jump height pre (cm)	Jump height post (cm)	Percentage change	p	Subgroup
Increase					
1	36.5 ± 1.6	41.6 ± 1.3	14	<0.01*	1
2	42.7 ± 1.5	47.4 ± 0.9	11	<0.01*	2
3	45.1 ± 1.4	49.6 ± 1.5	10	<0.01*	1
4	44.7 ± 1.9	48.4 ± 2.2	8	<0.01*	3
5	55.0 ± 1.8	59.0 ± 1.1	7	<0.01*	1
6	45.5 ± 1.8	48.4 ± 1.7	6	<0.01*	2
7	50.0 ± 2.2	52.3 ± 1.7	5	0.01*	3
8	45.1 ± 1.3	46.8 ± 1.1	4	0.02*	1
9	48.6 ± 1.3	50.1 ± 1.6	3	0.04*	2
No change					
1	44.4 ± 1.9	44.7 ± 1.8	1	0.71	1
2	51.5 ± 2.5	51.3 ± 1.4	0	0.78	2
3	45.9 ± 1.7	46.5 ± 1.2	1	0.28	3
4	42.3 ± 1.6	41.5 ± 1.7	-2	0.26	1
5	48.5 ± 1.9	47.1 ± 1.3	-3	0.22	2
6	48.4 ± 2.2	48.0 ± 1.2	-1	0.58	2
7	46.1 ± 2.0	47.0 ± 2.0	2	0.28	1
8	46.8 ± 0.7	45.8 ± 1.6	-2	0.06	1
9	45.8 ± 2.0	47.2 ± 1.8	3	0.06	3
10	44.1 ± 1.4	43.2 ± 1.1	-2	0.08	1
11	49.5 ± 1.4	50.5 ± 2.0	2	0.17	1
12	51.5 ± 1.7	50.3 ± 2.7	-2	0.10	2
13	43.1 ± 1.3	42.3 ± 1.8	-2	0.27	1
14	55.4 ± 1.1	53.0 ± 2.7	-4	0.44	1
15	41.4 ± 2.1	42.2 ± 1.4	2	0.23	2
16	53.1 ± 1.8	51.6 ± 0.8	-3	0.05	1
17	48.8 ± 1.1	47.6 ± 1.5	-2	0.23	3
18	45.0 ± 1.3	44.6 ± 1.9	-1	0.51	2
19	38.1 ± 1.2	36.8 ± 1.3	-3	0.11	1
20	55.1 ± 1.9	54.1 ± 1.7	-2	0.31	3
Decrease					
1	49.8 ± 1.5	44.1 ± 2.4	-11	<0.01*	1
2	51.9 ± 1.5	46.4 ± 3.4	-11	<0.01*	2
3	53.0 ± 1.7	47.7 ± 1.7	-10	<0.01*	2
4	54.6 ± 1.1	49.6 ± 1.4	-9	<0.01*	3
5	49.2 ± 1.8	46.1 ± 1.1	-6	<0.01*	1

* Significant difference pre versus post ($p<0.05$)

4.3.2. Group level

The primary aim of this study was to examine whether an analysis of the acute pre-training stress experienced by the group's CMJ PRFs in the DJ could give an insight into the effect that eight weeks of DJ training will have on CMJ jump height. More specifically, in light of the results presented in Table 4.1, could such an acute pre-training stress analysis have given an indication that the DJ would not improve this group's CMJ jump height?

Seven CMJ parameters were significantly ($p<0.05$) correlated with CMJ jump height (Table 4.3) and were therefore deemed to be CMJ PRFs for this group (step 1, Figure 2.9).

Table 4.3 The group's CMJ performance related factors

CMJ PRFs	Correlation with CMJ jump height r (p value)
1. Whole body concentric peak power	0.75 (<0.01)*
2. Whole body concentric work done	0.61 (<0.01)*
3. Time between peak power and takeoff	-0.53 (<0.01)*
4. Ankle concentric peak power	0.49 (<0.01)*
5. Time between joint reversal at the hip and knee	-0.46 (<0.01)*
6. Ankle rate of power development	0.43 (0.01)*
7. Knee angle at joint reversal ** †	-0.40 (0.01)*

* Significant correlation ($p<0.01$)

Negatively correlated with jump height - a smaller magnitude was associated with larger jump heights

† A more flexed knee at joint reversal (indicating a greater ROM) is associated with larger jump heights

The acute training stress experienced by each CMJ PRF in the DJ (DJ_{PRE} – CMJ_{PRE}) is identified in Table 4.4 (step 2, Figure 2.9). Based on this information, expected CMJ PRF post-training magnitude changes were proposed (Table 4.4, column F).

Whole body concentric peak power, ankle concentric peak power and ankle rate of power development were all deemed to have experienced an appropriate pre-training stress as their magnitudes were significantly greater ($p < 0.05$) in the DJ than in the CMJ (Table 4.4). The time between joint reversal at the hip and knee was significantly less ($p < 0.05$) in the DJ in comparison to the CMJ. This 70% difference was considered an appropriate training stress for this group as shorter times between joint reversals at the hip and knee were associated with larger CMJ jump heights (Table 4.4). Based on the pre-training stress experienced by each of these four CMJ PRFs they were all expected to experience an enhancement following training (Table 4.4, column F).

While the magnitudes of knee angle at joint reversal and the time between peak power and takeoff were significantly greater in the DJ in comparison to the CMJ (by 27% and 6%, respectively) they were considered to have experienced an inappropriate stress as both of these CMJ PRFs were negatively correlated with CMJ jump height (Table 4.4). Both knee angle at joint reversal and the time between peak power and takeoff were thus expected to experience post-training declines following training (Table 4.4, column F). Whole body concentric work done was significantly less in the DJ in comparison to the CMJ (Table 4.4) and was thus deemed to have not experienced an acute training stress and was not expected to change following DJ training (Table 4.4, column F).

The results of the pre-training stress analysis described above thus suggest a potential offset between CMJ PRF post-training enhancements and declines.

Table 4.4 Results of the acute pre-training stress analysis (DJ_{PRE}-CMJ_{PRE})

	A	B	C	D	E	F
CMJ PRFs	Pre CMJ (mean ± SD)	Pre DJ (mean ± SD)	Percentage difference	Significance (p)	Acute pre-training stress	Expected training effect
1. Whole body concentric peak power ($W. Kg^{-1}$)	49.0 ± 4.0	65.4 ± 9.2	33	<0.01*	Appropriate	Enhancement
2. Whole body concentric work done ($J.Kg^{-1}$)	7.9 ± 0.9	5.7 ± 0.7	-28	<0.01*	No stress	No change
3. Absolute time between peak power and takeoff (ms)	60.7 ± 5.7	64.2 ± 5.1	6	<0.01*	Inappropriate	Decline
4. Ankle concentric peak power ($W. Kg^{-1}$)	25.1 ± 4.8	35.8 ± 8.2	42	<0.01*	Appropriate	Enhancement
5. Absolute time between joint reversal at the hip and knee (ms)	43.9 ± 32.2	13.4 ± 10.7	-70	<0.01*	Appropriate	Enhancement
6. Ankle rate of power development ($W.kg^{-1}.s^{-1}$)	145 ± 63	457 ± 236	216	<0.01*	Appropriate	Enhancement
7. Knee angle at joint reversal (deg) †	79.6 ± 11.1	101 ± 7.5	27	<0.01*	Inappropriate	Decline

* Significant difference CMJ pre versus DJ pre ($p<0.05$)

Red: PRF negatively correlated with jump height means a smaller magnitude is associated with larger jump heights

† A more flexed knee at joint reversal (indicating a greater ROM) is associated with larger jump heights

Sub-aim ‘a’ of this study was to determine if the acute pre-training training stress experienced by the CMJ PRFs in the DJ could explain the post-training magnitude change in these same CMJ PRFs following eight weeks of training. The post-training changes experienced by the group’s CMJ PRFs are outlined in Table 4.5. A comparison of the expected CMJ PRF post-training changes (based on the pre-training analysis) versus the actual post-training CMJ PRF changes is provided in Table 4.6. Expected post-training magnitude changes were found to be accurate for five out of the seven CMJ PRFs under investigation (Table 4.6, Column D). Two expected post-training magnitude changes were inaccurate. The time between joint reversal at the hip and knee experienced an appropriate pre-training stress in the DJ but, unexpectedly, did not enhance after the DJ training period (Table 4.6). The time between peak power and takeoff experienced an inappropriate pre-training stress in the DJ yet unexpectedly did not change following training (Table 4.6). In addition, no significant correlation was found between the magnitude of pre-training stress experienced by a given CMJ PRF in the DJ ($DJ_{PRE} - CMJ_{PRE}$) and its post-training change ($CMJ_{POST} - CMJ_{PRE}$) [Table 4.7].

Table 4.5 CMJ PRF magnitude changes following the eight weeks of drop jump training

CMJ PRFs	Pre CMJ (mean ± SD)	Post CMJ (mean ± SD)	Percentage Difference	Post-training change
1. Whole body concentric peak power (W. Kg^{-1})	49.0 ± 4.0	50.5 ± 4.2 *	3	Enhancement
2. Whole body concentric work done (J.Kg^{-1})	7.9 ± 0.9	8.1 ± 0.8	2	No change
3. Time between peak power and takeoff (ms)	60.7 ± 5.7	61.0 ± 5.8	1	No change
4. Ankle concentric peak power (W. Kg^{-1})	25.1 ± 4.8	27.8 ± 4.9 *	11	Enhancement
5. Time between joint reversal at the hip and knee (ms)	43.9 ± 32.2	47.3 ± 28.3	8	No change
6. Ankle rate of power development (W.kg^{-1}.s^{-1})	145 ± 63	181 ± 56 *	25	Enhancement
7. Knee angle at joint reversal (deg) †	79.6 ± 11.1	84.7 ± 8.1 *	6	Decline

* Significant within group (pre vs. post) and between group (training vs. control) change ($p<0.05$)
Red: PRF negatively correlated with jump height means a smaller magnitude is associated with larger jump heights
† A more flexed knee at joint reversal is associated with larger jump heights

Table 4.6 A comparison of expected versus actual CMJ PRF post-training magnitude changes

	A	B	C	D
CMJ PRFs	Pre-training stress	Expected training effect	Actual training effect	Accuracy of expected training effect
1. Whole body concentric peak power	Appropriate	Enhancement	Enhancement	Accurate
2. Whole body concentric work done	No stress	No change	No change	Accurate
3. Time between peak power and takeoff	Inappropriate	Decline	No change	Inaccurate
4. Ankle concentric peak power	Appropriate	Enhancement	Enhancement	Accurate
5. Time between joint reversal at the hip and knee	Appropriate	Enhancement	No change	Inaccurate
6. Ankle rate of power development	Appropriate	Enhancement	Enhancement	Accurate
7. Knee angle at joint reversal †	Inappropriate	Decline	Decline	Accurate

† A more flexed knee at joint reversal (indicating a greater ROM) is associated with larger jump heights

Red: PRF negatively correlated with jump height means a smaller magnitude is associated with larger jump heights

Table 4.7 Correlation (r) between the acute-pre training stress experienced by a CMJ PRF (DJ_{PRE}-CMJ_{PRE}) and its post training change (CMJ_{POST} – CMJ_{PRE})

CMJ PRFs	r	P
1. Whole body concentric peak power	-0.08	0.64
2. Whole body concentric work done	0.01	0.95
3. Time between peak power and takeoff	0.05	0.78
4. Ankle concentric peak power	0.36	0.06
5. Time between joint reversal at the hip and knee	0.24	0.18
6. Ankle rate of power development	0.03	0.86
7. Knee angle at joint reversal	0.10	0.56

Sub-aim 'b' of this study was to examine if the post- training magnitude change experienced by the group's CMJ PRFs following eight weeks of drop jump training could explain the post-training change in the group's CMJ jump height. More specifically, could the post-training changes experienced by the CMJ PRFs explain the lack of CMJ jump height change? The post-training change experienced by each of the group's CMJ PRFs has already been presented in Table 4.5. Three of the seven CMJ PRFs did not experience a magnitude change, three others enhanced, while one CMJ PRF, knee angle at joint reversal, declined significantly ($p<0.05$).

The correlations between the post-training change in CMJ jump height and the post-training magnitude change in each of the seven CMJ PRFs are presented in Table 4.8. A significant positive correlation was found between post-training training change (CMJ_{POST} – CMJ_{PRE}) in CMJ jump height and the post-training change in both whole body concentric peak power and whole body concentric work done, respectively (Table 4.8, Figures 4.1 and 4.2). A significant negative correlation was found between post-training change in CMJ jump height and the change in the time between peak power and takeoff (Table 4.8, Figure 4.3). The latter negative correlation implies that reductions in the time between peak power and takeoff were associated with increases in CMJ jump height.

Table 4.8 Correlation (r) between the post-training change in a CMJ PRF ($CMJ_{POST} - CMJ_{PRE}$) and the post training change in CMJ jump height ($CMJ_{POST} - CMJ_{PRE}$)

CMJ performance related factors	r	Significance (p)
1. Whole body concentric peak power	0.34 *	0.05
2. Whole body concentric work done	0.44 *	0.02
3. Time between peak power and takeoff	-0.48 *	<0.01
4. Ankle concentric peak power	0.07	0.70
5. Time between joint reversal at the hip and knee	0.11	0.53
6. Ankle rate of power development	0.03	0.87
7. Knee angle at joint reversal	-0.04	0.82

* Significant correlation ($p<0.05$)

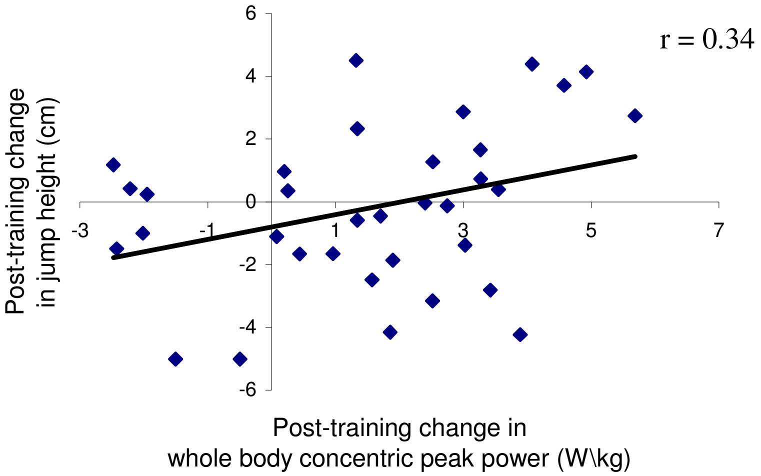

Figure 4.1 Scatter plot of the relationship between the post-training change in whole body concentric peak power and the post-training change in CMJ jump height

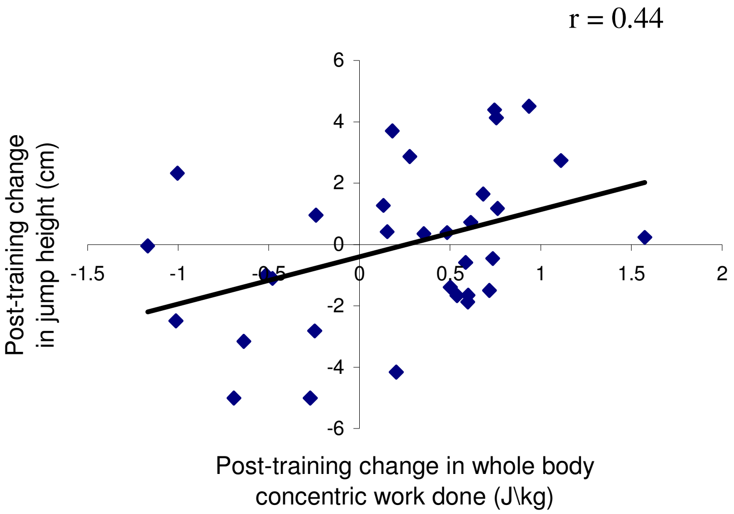

Figure 4.2 Scatter plot of the relationship between the post-training change in whole body concentric work done and the post- training change in CMJ jump height

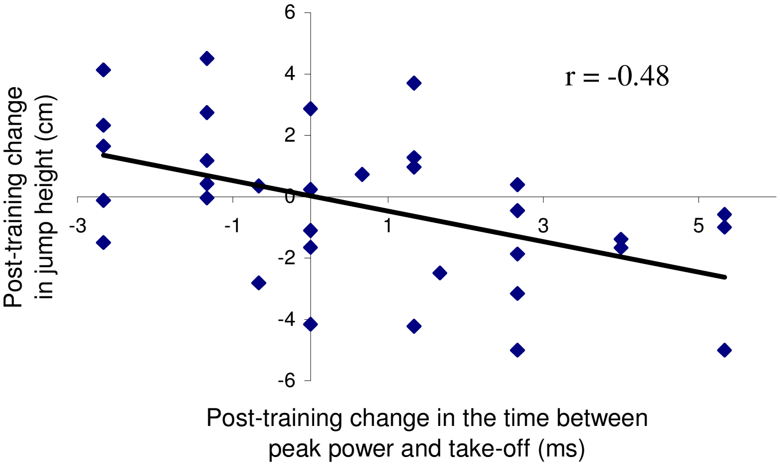

Figure 4.3 Scatter plot of the relationship between the post-training change in the time between peak power and takeoff and the post training change in CMJ jump height

4.3.3 Subgroup level

Individuals were initially subgrouped based on the magnitude of pre-training stress they experienced in the DJ. Only five of the seven CMJ PRFs were used in the cluster analysis (Table 4.9). Two parameters, ankle concentric peak power and ankle rate of power development, were highly correlated with whole body concentric peak power (r = 0.74 and r = 0.72, respectively) and were thus excluded.

Table 4.9 CMJ parameters used in the cluster analysis

CMJ parameters
1. Whole body concentric peak power
2. Whole body concentric work done
3. Absolute time between peak power and takeoff
4. Absolute time between joint reversal at the hip and knee
5. Knee angle at joint reversal (deg)

The dendrogram produced by the cluster analysis is provided in Figure 4.4. A relatively large increase in the agglomeration coefficient occurred between the three subgroup and two subgroup solutions (27% increase) [Table 4.10], indicating that a three-cluster solution was appropriate. Solution validity was examined by checking for between subgroup differences in the magnitude of pre-training stress which was confirmed with a significant MANOVA Wilks' $\gamma = 0.08, p<0.001$.

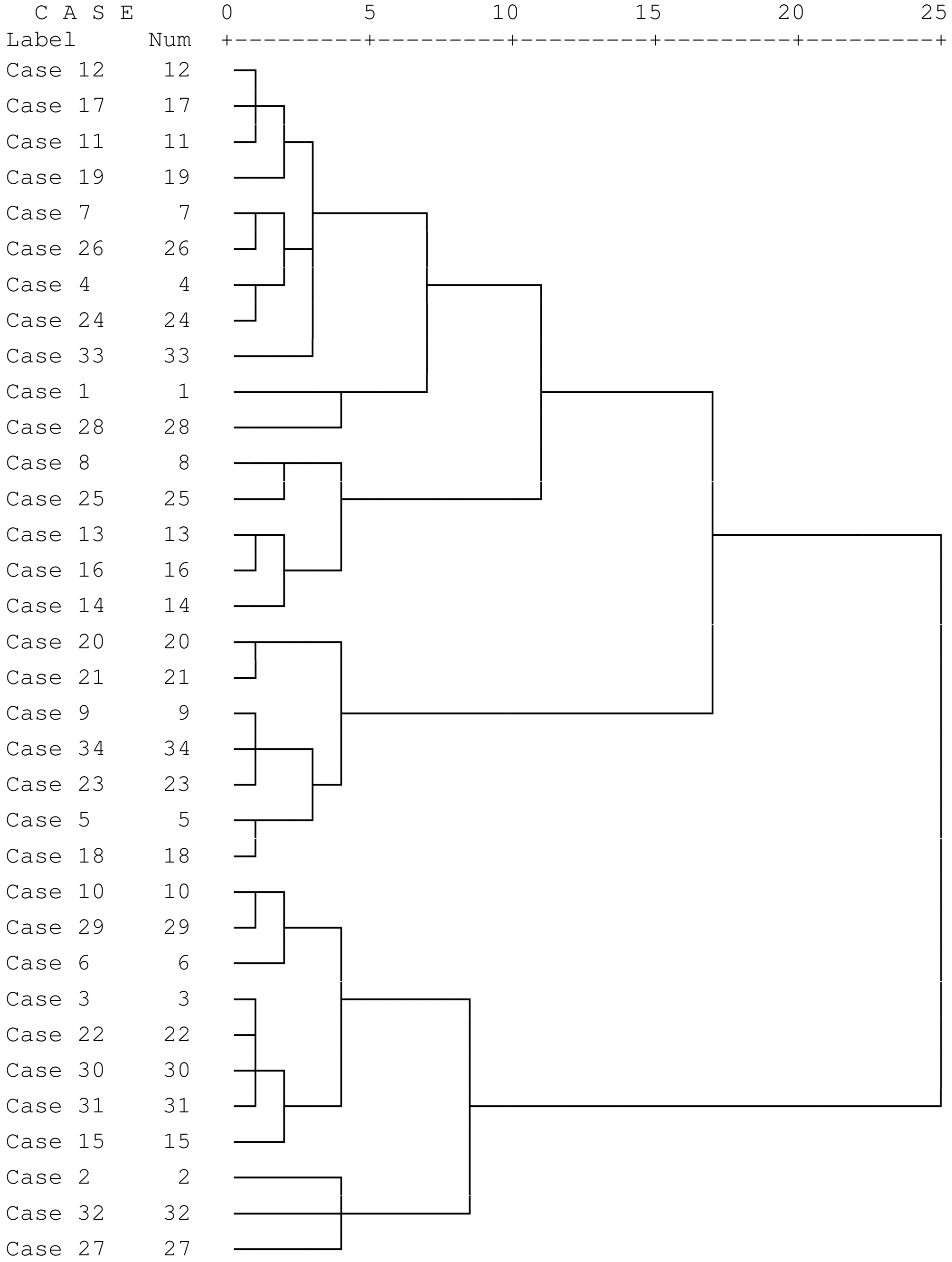

Figure 4.4 Dendrogram produced in the Wards method hierarchal cluster analysis

Table 4.10 Change in the agglomeration coefficient as the number of subgroups changed

Change in number of subgroups	Agglomeration coefficient	Percentage change in agglomeration coefficient
7 to 6	64.5	11
6 to 5	74.3	15
5 to 4	88.1	19
4 to 3	105.0	19
3 to 2	133.0	27
2 to 1	165.0	25

The three subgroups created did not experience a post-training change in CMJ jump height (Table 4.11). In light of these findings, the primary aim of this study was to examine whether the acute pre-training stress experienced by each respective subgroup could have given an indication that the DJ would not improve each subgroup's CMJ jump height.

Table 4.11 Subgroup mean change (± SD) in CMJ jump height pre to post-training

	Change in CMJ height (cm) [$CMJ_{POST} - CMJ_{PRE}$]
Subgroup 1	0.2 ± 2.2
Subgroup 2	-1.0 ± 3.1
Subgroup 3	0.1 ± 2.8
Between subgroup Differences	No

Between subgroup differences in the magnitude of pre-training stress (DJ_{PRE} - CMJ_{PRE}) experienced by the CMJ PRFs in the DJ are outlined in Table 4.12. Table 4.12 also details the actual pre-training stress (appropriate, inappropriate or no training stress) experienced by the CMJ PRFs in each subgroup. Based on this latter information it was possible to outline the likely post-training magnitude change that each CMJ PRF would experience (for each subgroup) following training (Table 4.13). While numerous between subgroup differences were evident in the magnitude of pre-training stress experienced (DJ_{PRE} - CMJ_{PRE}), the actual pre-training stress experienced by CMJ PRFs (appropriate, inappropriate or no training stress) was subject to much less between subgroup variation (Table 4.12). For example, peak power was appropriately stressed in each subgroup,

Table 4.12 The magnitude of pre-training stress (DJ_{PRE} - CMJ_{PRE}) experienced by each subgroup in the drop jump

	Whole body concentric peak power ($W.kg^{-1}$)	Whole body concentric work done ($J.kg^{-1}$)	Time between peak power and takeoff (ms) †	Time between joint reversal at the hip and knee (ms)	Knee angle at joint reversal (degrees)
Subgroup 1 (n = 16)	11.9 ± 4.6 Appropriate stress *	-1.7 ± 0.7 No stress *	4.9 ± 3.4 Inappropriate stress *	-35.3 ± 46.9 Appropriate stress *	16.7 ± 8.2 Inappropriate stress *
Subgroup 2 (n = 11)	25.2 ± 5.6 Appropriate stress *	-2.5 ± 0.7 No stress *	0.7 ± 2.6 No stress	-16.5 ± 45.8 Appropriate stress *	26.1 ± 10.5 Inappropriate stress *
Subgroup 3 (n = 7)	11.0 ± 3.8 Appropriate stress *	-2.8 ± 0.7 No stress *	6.9 ± 2.6 Inappropriate stress *	6.1 ± 26.9 No stress	28.6 ± 3.4 Inappropriate stress *
Between subgroup stress differences ($p < 0.05$)	2 > 1,3	1 > 2,3	1,3 > 2	None	2,3 > 1

* Significant difference DJ magnitude vs. CMJ magnitude ($p<0.05$)

Red: PRF negatively correlated with jump height - a smaller magnitude is associated with larger jump height

Table 4.13 The CMJ PRF magnitude changes that each subgroup was expected to experience following the training period

	Whole body concentric peak power ($W.kg^{-1}$)	Whole body concentric work done ($J.kg^{-1}$)	Time between peak power and takeoff (ms) †	Time between joint reversal at the hip and knee (ms)	Knee angle at joint reversal (degrees)
Subgroup 1	Enhance	No change	Decline	Enhance	Decline
Subgroup 2	Enhance	No change	No change	Enhance	Decline [2]
Subgroup 3	Enhance [1]	No change	Decline	No change	Decline [2]

[1] Subgroup 3 enhancement > Subgroup 2 and 1 enhancement

[2] Subgroup 2 and 3 decline > subgroup 1 decline

work done was not stressed in each subgroup and knee angle at joint reversal was inappropriately stressed in each subgroup (Table 4.12). In light of the subgroup similarities in the nature of the pre-training stress experienced, the expected post-training CMJ PRF changes were quite similar across subgroups. For example, each subgroup was expected to experience an increase in whole body concentric peak power, a decline in the knee angle at joint reversal and no change in whole body concentric work done (Table 4.13). Indeed similar to what was found at the group level the pre-training stress experienced by each subgroup would suggest a potential offset between CMJ PRF post-training enhancements and declines (Table 4.13).

Sub-aim ‘a’ of this study was to determine if the acute pre-training training stress experienced by the CMJ PRFs in the drop jump could explain the post-training magnitude change in these same CMJ PRFs following eight weeks of training. Similar to that found at the group level, the expected post-training changes in peak power, work done and knee angle at joint reversal (Table 4.13) subsequently occurred in each subgroup (Table 4.14). Again similar to that found at the group level, the predicted post-training changes in (a) the time between peak power takeoff, and (b) the time between joint reversal at the hip and knee (Table 4.13), were generally inaccurate (Table 4.14). Despite the numerous between subgroup differences in the magnitude of pre-training stress experienced by the CMJ PRFs in the DJ (Table 4.13) there were no between subgroup differences in post-training CMJ PRF magnitude changes (Table 4.14). This latter finding was based on a non-significant MANOVA; Wilks’ $\gamma = 0.79$, $p = 0.4$.

Sub-aim ‘b’ of this study was to examine whether the post-training magnitude changes experienced by the CMJ PRFs ($CMJ_{POST} - CMJ_{PRE}$) in a particular subgroup could explain that subgroup’s post-training change in CMJ jump height ($CMJ_{POST} - CMJ_{PRE}$). Each of the three subgroups experienced a post-training increase in whole body concentric peak power, a post-training decline in knee angle at joint reversal and no post-training change in the remaining CMJ PRFs (see Table 4.14).

Table 4.14 The actual CMJ PRF post-training magnitude changes (CMJ_{POST} - CMJ_{PRE}) experienced by each subgroup

	Whole body concentric peak power ($W.kg^{-1}$)	Whole body concentric work done ($J.kg^{-1}$)	Time between peak power and takeoff (ms)†	Absolute time between joint reversal at the hip and knee (ms)	Knee angle at joint reversal (degrees)
Subgroup 1	1.1 ± 2.2 Enhancement *	0.2 ± 0.8 No change	-0.3 ± 3.5 No change	0.9 ± 28.5 No change	5.0 ± 7.7 Decline *
Subgroup 2	1.2 ± 2.6 Enhancement *	0.3 ± 0.9 No change	1.3 ± 3.2 No change	-2.5 ± 29.8 No change	3.0 ± 6.0 Decline *
Subgroup 3	2.1 ± 2.0 Enhancement *	0.2 ± 0.7 No change	0.4 ± 1.8 No change	15.7 ± 14.4 No change	8.9 ± 5.3 Decline *
Between subgroup Differences	None	None	None	None	None

* Significant within group post-training change ($p<0.05$)

Red: PRF negatively correlated with jump height means a smaller magnitude is associated with larger jump heights

4.3.4 Individual level

The primary aim of this study was to examine whether an analysis of the acute pre-training stress experienced by an individual's CMJ PRFs in the DJ could give an insight into the effect that eight weeks of DJ training will have on that individual's CMJ jump height. As indicated previously nine individuals significantly ($p<0.01$) improved their CMJ jump height, twenty had no significant change and for five individuals their CMJ jump height significantly reduced (Table 4.2). Rather than presenting the results of all individuals, the results of five individuals who significantly ($p<0.01$) improved their CMJ jump height, five individuals with no significant change in CMJ jump height and five individuals with a significant reduction in CMJ jump height are presented. The results for these individuals (individuals A-O) are outlined in Tables A1-A15 in Appendix A. Each table details each individual's CMJ PRFs, the acute-training stress the CMJ PRFs experienced in the DJ, the post-training change that the CMJ PRFs were expected to experience and the actual post-training change that the CMJ PRFs did experience.

No common pattern was found between the pre-training stress experienced by an individual's CMJ PRFs (DJ_{PRE} - CMJ_{PRE}) and that individual's post-training jump height change (CMJ_{POST} - CMJ_{PRE}) [Tables A1-A15]. While individual B (Table A2), an improver, had nine out of ten CMJ PRFs appropriately stressed, individual E (Table A5), also an improver, had no CMJ PRFs appropriately stressed. Similar findings, where the pre-training analysis gave no indication of post-training change, were also found for individuals who had no change or a significant reduction in jump height. Individual F (Table A6), an individual with no change in jump height, had six out of nine CMJ PRFs appropriately stressed while individual M (Table A13), a reducer, did not experience any inappropriate pre-training stresses.

Sub-aim 'a' of this study was to determine if the acute pre-training training stress experienced by a given individual's CMJ PRFs in the DJ could explain the post-training magnitude change in these same CMJ PRFs following eight weeks of training. At the individual subject level, expected CMJ PRF post-training magnitude changes were found to be inaccurate in over half of all cases (Tables A1-A15, Column F). In total 112 expected CMJ PRF post-training magnitude changes were proposed of which 59% were inaccurate. Whole body concentric peak power experienced a significant pre-training stress ($p<0.05$) in the DJ for individual K, for example, but actually significantly declined following training ($p<0.05$) [Table A11].

Sub-aim 'b' of this study was to examine if the post-training magnitude change experienced by an individual's CMJ PRFs following eight weeks of drop jump training could explain the post- training change in that individual's CMJ jump height. No common pattern was found between the post-training change experienced by an individual's CMJ PRFs and that individual's post-training jump height change (Tables A1 to A15). While all of the CMJ jump height improvers (individuals A-E, Tables A1-A5) had numerous post-training enhancements in CMJ PRFs, some individuals with no post-training increase in jump height and indeed some with a post-training reduction in jump height also had post-training CMJ PRF enhancements. Individual G (no change in jump height) had post-training enhancements in four CMJ PRFs while Individual M (a reducer) also had enhancements in four CMJ PRFs [Tables A7 and A13, respectively].

4.4 Discussion

The previous study (study 1) demonstrated that the proposed pathway may be able to identify the most appropriate training exercise to enhance a given group's, subgroup's or individual's CMJ jump height. However, these findings were based on the untested hypothesis that an acute pre-training stress analysis (which utilises statistical relationships and differences) can provide an insight into the training effect that a given exercise will have on CMJ jump height. A pre-training stress analysis involves identifying the training stress experienced by CMJ PRFs in a given training exercise and using this information to propose the likely training effects of that exercise (see section 2.4 for more details). In addition, two inherent assumptions of such an analysis remain untested: (i) that the pre-training stress experienced by a given CMJ PRF will give an insight into its post-training magnitude change, and (ii) that CMJ performance related factors (PRFs) are likely to be true CMJ performance determining factors (PDFs) [see section 2.2.2 for more details on the distinction between PRFs and PDFs]. The current study aimed to examine these respective hypotheses (at a group, subgroup and individual-subject level) using an eight-week drop jump training study.

4.4.1 Group level

In the current study eight weeks of drop jump (DJ) training did not improve the group's mean CMJ jump height (see Table 4.1). This finding is similar to that of Young et al. (1999) but is in contrast with the findings of a number of studies, including Gehri et al. (1996) who found a significant 8% improvement in CMJ jump height after DJ training (see Table 2.24). The primary aim of this study was to examine whether an analysis of the acute pre-training stress experienced by the group's CMJ PRFs in the DJ could give an insight into the effect that eight weeks of DJ training will have on CMJ jump height. More specifically, in light of the lack of post-training jump height change observed in this study, could the acute pre-training stress analysis have given an indication that the DJ would not improve this group's CMJ jump height? Based on the pre-training stress analysis four CMJ PRFs were expected to enhance following training, one was not expected to change while two others were expected to experience post-training declines (Table 4.4). These pre-training results suggested a potential offset between CMJ PRF post-training enhancements and declines and as such the DJ would not have been expected to induce a notable post-training increase in CMJ jump height (hypothesis one supported). In light of these findings it could be suggested that an analysis of the pre-training stress that CMJ PRFs experience in a given training exercise may provide an insight into the training effect that that exercise may have on CMJ jump height. More training studies are required to provide further evidence to support this theory and it would be desirable if such studies found a post-training enhancement in CMJ jump height.

Evidence that the expected offsetting phenomenon actually occurred in this study is provided in Table 4.5. Post-training enhancements ($p<0.05$) in peak whole body power (3%), ankle power (11%) and ankle rate of power development (25%) did not lead to a post-training enhancement in jump height. It is proposed that these enhancements were offset, at least in part, by the significant ($p<0.05$) 6% decline in knee range of motion (Table 4.5). Previous studies have also found a period of DJ training effective at enhancing whole body concentric peak power (Holcomb et al. 1996b; Leubbers et al. 2003; Potteiger et al. 1999). For example, Holcomb et al. (1996b) reported a significant 6.5% increase in CMJ peak power following eight weeks of DJ training. It would appear however, that the present study is the first study to report significant post-training changes in ankle concentric peak power, ankle rate of power development and knee angle at joint reversal following a period of DJ training. The finding that knee angle at joint reversal changed significantly following training confirms the notion that training exercises traditionally employed to enhance aspects of CMJ neuromuscular capacity may also negatively influence aspects of jumping technique (see section 2.3.1). It would appear that repeatedly undertaking a DJ with a small amount of knee flexion led to a learning effect whereby the CMJ began to exhibit this same characteristic.

Bobbert et al. (1987) theorise that if athletes regularly practise the CMJ throughout a training period they may prevent unwanted CMJ technique and coordination changes. It could be suggested therefore that if the subjects in the current study regularly carried out CMJ repetitions over the course of the eight-week training period the reduction in CMJ knee joint of motion could have been prevented and jump height may have improved. However, no complimentary CMJ repetitions were prescribed in this study so that training induced gains could be attributed to the DJ training alone.

An underlying assumption of the pre-training stress analysis is that the training stress experienced by a given CMJ PRF (appropriate, inappropriate or no training stress) will give an insight into the post-training magnitude change that that same

CMJ PRF will experience (see section 2.4). Sub-aim 'a' of the current study investigated this hypothesis by examining whether the acute pre-training training stress experienced by CMJ PRFs in the DJ could explain the post-training magnitude change in these same CMJ PRFs. While the majority (five) of the proposed post-training changes were accurate, another two were found to be inaccurate (Table 4.5). The time between joint reversal at the hip and knee experienced an appropriate pre-training stress in the DJ but, unexpectedly, did not enhance after the DJ training period (Tables 4.6). The time between peak power and takeoff experienced an inappropriate pre-training stress in the DJ yet surprisingly did not change following training (Tables 4.6). The two inaccurate post-training change predictions may however be readily explained:

(1) While the time between joint reversal at the hip and knee was deemed to have experienced a significant appropriate pre-training stress in the DJ ($p<0.05$), it may in fact have experienced no training stress due to a lack of training specificity. Both hip and knee joint angles at joint reversal were significantly ($p<0.05$) more extended in the DJ, by 69° and 21° respectively, than in the CMJ. Thus, when identifying the pre-training stress experienced by such coordination based CMJ PRFs in the DJ, associated joint angles may also have to be taken into consideration.

(2) While the time between peak power and takeoff experienced a significant inappropriate pre-training stress in the DJ ($p<0.05$) this training stress may not have been large enough to elicit a detrimental training effect. The time between peak power and takeoff was only 6% greater in the DJ than in the CMJ. Other statistically significant training stresses, which led to expected post-training changes (Table 4.6), were of a much larger magnitude (no less than 27% difference, Table 4.4). Thus, when identifying the pre-training stress experienced by this CMJ PRF, a significant training stress may only be functionally significant when it is above a certain threshold value.

From points one and two above it appears that the inaccurate post-training change predictions evident in this study could be prevented in future studies. It may be suggested therefore that an analysis of the pre-training stress experienced by a given CMJ PRF in a given training exercise may provide an insight into its post-training change. While this finding is in accordance with the theory of training overload (Zatsiorsky and Kraemer 2006) no other studies have examined such a link between pre-training stress and post-training change. Further training studies are required to determine whether the unexpected post-training changes found in this study are isolated instances or are evident in other CMJ PRFs. Clearly, a greater number of inaccurate post-training change predictions will reduce the efficacy of the proposed biomechanical pathway.

No significant correlations were found between the magnitude of training stress experienced by a given CMJ PRF ($DJ_{PRE} - CMJ_{PRE}$) and the post-training magnitude change experienced by that same CMJ PRF ($CMJ_{POST} - CMJ_{PRE}$) [Table 4.7]. These findings, in conjunction with those discussed above, suggest that while a training stress may need to be above a certain magnitude threshold to elicit a training effect, greater magnitudes of training stress beyond this threshold may not lead to greater training effects. The major implication of this finding is that when comparing training stresses between different training exercises (step 2, Figure 2.9) it may be appropriate to base the comparison solely on differences in the actual training stress experienced by a given CMJ PRF (appropriate, inappropriate or no training stress). Before this, in line with that suggested by Bobbert et al (1987a), when one training exercise appropriately stressed a CMJ PRF to a greater extent than another it was expected to induce a greater post-training magnitude change in that CMJ PRF (see study 1 methods section 3.2.6, pg103). The results of the present study, the only study to examine this issue with a training study, do not support this view.

Sub-aim ‘b’ of the current study examined whether the post-training change experienced by the group’s CMJ PRFs ultimately determined the group’s post-training change in CMJ jump height. In other words, could the CMJ PRFs identified in step one of the pathway (Figure 2.9) be considered to be true CMJ PDFs? This was investigated in two ways: (a) by examining whether the cumulative post-training changes experienced by the group's CMJ PRFs could explain the post-training change in CMJ jump height, and (b) by correlating the post-training magnitude change of each CMJ PRF with the magnitude of CMJ jump height change (Table 4.8).

As detailed in Table 4.5 three CMJ PRFs enhanced following training, another three did not change and one, knee angle at joint reversal, experienced a post-training decline. As already outlined above it is proposed that the post-training enhancements in whole body peak power, ankle peak power and ankle rate of power development did not lead to an increase in CMJ jump height as they were offset by the more extended knee angle at joint reversal (indicating a smaller knee range of motion). This, in combination with the fact that another three CMJ PRFs did not experience a post-training change would appear to explain why there was no change in the group's CMJ jump height. These findings suggest that the seven CMJ PRFs identified for this group are collectively determining CMJ jump height and could thus be considered true CMJ PDFs. More training studies are required to provide further evidence to support this theory and it would be desirable if such studies found a post-training enhancement in CMJ jump height.

To further examine the extent to which the seven identified CMJ PRFs (Table 4.3) were likely to be true CMJ PDFs the magnitude of CMJ PRF change and the magnitude of jump height change were examined for correlations. To this author's knowledge no previous studies have attempted to examine this issue. Significant correlations ($p<0.05$) were found for whole body concentric peak power, whole body concentric work done and the time between peak power and takeoff (Table 4.8). These findings provide compelling evidence to suggest that these three CMJ PRFs were indeed true CMJ PDFs for this group. The post-training changes in each of the remaining four CMJ PRFs were not significantly correlated with CMJ jump height change (Table 4.8), however these findings do not necessarily imply that these CMJ PRFs were not true CMJ PDFs. The post-training change correlation analysis only examines if a linear relationship between the change in one CMJ PRF and the change in CMJ jump height exists. It may be more likely however, as suggested previously with the offsetting theory, that changes in CMJ PRFs collectively influence CMJ jump height. This concept is supported with the results of a regression analysis that showed that the collective post-training changes in the seven CMJ PRFs were strongly related to the post-training change in CMJ jump height ($r = 0.75$, $p<0.004$).

The fact that the respective hypotheses concerning sub-aims 'a' and 'b' (at a group level) were supported in this study lends further credence to the suggestion that a pre-training stress analysis can provide an insight into the training effect that a given exercise will have on a group's CMJ jump height. This, in conjunction with the findings of the previous study, would suggest that the proposed biomechanical diagnostic and prescriptive pathway (Figure 2.9) may be able to identify the most effective training exercise to enhance a given group's CMJ jump height.

4.4.2 Subgroup level

The primary aim of this study (at the subgroup level) was to examine whether the acute pre-training stress experienced by the CMJ PRFs in each respective subgroup could explain each subgroup's post-training CMJ jump height change. More specifically, in light of the fact that none of the subgroups created experienced a post-training change in jump height (Table 4.11), could the acute pre-training stress experienced by the subgroups in the DJ have given an indication that the DJ would not improve their respective CMJ jump heights? As found at the group level, the pre-training stress results for each respective subgroup (Table 4.12) suggested a potential offset between CMJ PRF post-training enhancements and declines. As such, the DJ would not have been expected to induce a notable post-training increase in jump height for any of the subgroups. These findings suggest that an analysis of the pre-training stress experienced by the CMJ PRFs in a given subgroup may provide an insight into that subgroup's post-training CMJ jump height change. As at the group level, further studies are required to provide more evidence to support this theory and it would be desirable if some of the subgroups in such studies experienced a post-training enhancement in CMJ jump height.

Evidence that the expected offsetting phenomenon actually occurred in each subgroup is provided in Table 4.14. Each subgroup experienced a significant ($p<0.05$) post-training increase in whole body concentric peak power but a significant ($p<0.05$) decline in knee angle at joint reversal while none of the remaining CMJ PRFs experienced a post-training change for each subgroup.

Sub-aim ‘a’ of the current study examined whether the acute pre-training training stress experienced by the CMJ PRFs in the DJ could explain the post-training magnitude change in these same CMJ PRFs following eight weeks of training. Again similar to that found at the group level the expected post-training changes experienced by knee angle at joint reversal, whole body concentric peak power and whole body concentric work done were found to be accurate (Tables 4.13 and 4.14). In contrast, the expected post-training changes experienced by the time between peak power and takeoff and the time between joint reversal at the hip and knee were often inaccurate (see Tables 4.13 and 4.14). For example, the time between peak power and takeoff experienced an inappropriate pre-training stress for subgroups one and two (Table 4.13), but neither subgroup experienced a post-training decline in this CMJ PRF (Table 4.14). The same explanations put forward in the group level discussion (points one and two, pg167) may also explain these unexpected post-training CMJ PRF magnitude changes. As such, these inaccurate post-training change predictions may be prevented in future studies. It could be suggested therefore, in accordance with the theory of training overload (Zatsiorsky and Kraemer 2006), that the pre-training stress experienced by a given CMJ PRF in a given training exercise may provide an insight into the post-training change that this same CMJ PRF will experience.

Of note, despite between subgroup differences in the magnitude of pre-training stress experienced by a given CMJ PRF (Table 4.12), there were no between subgroup differences in the post-training magnitude change experienced by any of the CMJ PRFs (Table 4.14). That is, while individuals were successfully subgrouped into homogenous subgroups based on the magnitude of training stress they experienced, each subgroup responded in the same way to the DJ training stimulus. These findings lend further support to the stress threshold theory proposed above in the group level discussion. This theory proposes that while a training stress may need to be above a certain magnitude threshold to elicit a training effect, greater magnitudes of training stress beyond this threshold may not lead to greater training effects. The major implication of this finding, at the subgroup level, is that when comparing training stresses between different subgroups it may be appropriate to base the comparison solely on differences in the actual training stress experienced by a given CMJ PRF (appropriate, inappropriate or no training stress). Currently, between subgroup comparisons in the training stress experienced by a given CMJ PRF are based on differences in the actual training stress experienced (appropriate, inappropriate or no stress) and differences in the magnitude of training stress (see study 1 methods section 3.2.6, pg103). The findings of the current study do not support the suggestion of Bobbert et al. (1987a) that when a training exercise appropriately stresses a CMJ parameter to a greater extent than another it is likely to induce a greater post-training magnitude change in that CMJ PRF.

Sub-aim ‘b’ of this study was to examine whether the post-training magnitude changes experienced by the CMJ PRFs in a particular subgroup could explain that subgroup’s post-training change in CMJ jump height. As outlined previously, each subgroup experienced a significant ($p<0.05$) post-training increase in whole body concentric peak power, a significant ($p<0.05$) decline in knee angle at joint reversal and no change in the remaining CMJ PRFs. It would appear therefore, similar to that found at the group level, that a post-training CMJ PRF increase was offset by a post-training CMJ PRF decline in each subgroup. These findings support the suggestion that the CMJ PRFs (identified in the group analysis) could be considered true CMJ PDFs for each of the three subgroups created.

The fact that the respective hypotheses concerning sub-aims ‘a’ and ‘b’ (at the subgroup level) were supported in this study, lends further credence to the suggestion outlined above (aim one) that an analysis of the pre-training stress experienced by CMJ PRFs in a given subgroup may provide an insight into that subgroup’s post-training CMJ jump height change. This, in conjunction with the findings of study one, would suggest that by applying the proposed biomechanical diagnostic and prescriptive pathway (Figure 2.9), using both a group and subgroup analysis, one may be able to identify the most effective training exercise to enhance a given subgroup’s CMJ jump height.

4.4.3 Individual level

The findings of study one of this thesis suggest that it might be possible to identify the most appropriate exercise for a given individual, by applying the proposed pathway (Figure 2.9) using a single-subject analysis. However, these findings were based on the untested hypothesis that a pre-training stress analysis can provide an insight into the training effect that a particular exercise will have on a given individual’s jump height. The current study tested this hypothesis by examining whether an analysis of the acute pre-training stress experienced by an individual’s CMJ PRFs in the DJ could give an insight into the effect that eight weeks of DJ training will have on that individual’s CMJ jump height.

The present study found that there was no consistent pattern between the pre-training stress experienced by an individual’s CMJ PRFs and an individual’s post-training change in jump height (see Tables A1 to A15, Appendix A). For example, individual E had a significant 5% increase ($p<0.05$) in CMJ jump height following DJ training yet none of his identified CMJ PRFs experienced an appropriate pre-training stress (Table A5, Appendix A). These findings indicate, contrary to what was found at the group and subgroup level, that an analysis of the acute pre-training stress experienced by an individual’s CMJ PRFs may not give an insight into the effect that a given training exercise will have on an individual’s CMJ jump height. In order to explain these findings it is necessary to examine the outcomes of both sub-aim ‘a’ and sub-aim ‘b’.

Sub-aim ‘a’ of this study was to determine if the acute pre-training training stress experienced by a given individual’s CMJ PRFs in the DJ, could explain the post-training magnitude change in these same CMJ PRFs following training. As evident from Tables A1 to A15 (Appendix A), no common pattern was found between the pre-training stress experienced by a given individual’s CMJ PRFs and the post-training magnitude change in these same CMJ PRFs. These findings, which are in contrast to those at the group and subgroup level, may be explained, in part, by complications arising at the individual subject level. Latash et al. (2007), for example, suggests that the neuromuscular system may allow a high level of co-variance in elemental variables in order to stabilise other performance variables (Latash et al. 2007). This is in accordance with the dynamical systems theory of intra-subject variability (see section 2.4.2, pg82). Such functional parameter covariation may be responsible, in part, for some of the inaccurate CMJ PRF magnitude change predictions found in this study. Additionally, as outlined in section 2.2.10, numerous biomechanical constraints limit how a given individual produces a CMJ (Van Ingen Schenau 1989). It is likely, therefore, that an individual’s neuromuscular system must manage post training CMJ PRF magnitude changes very carefully. Such management may entail preventing the manifestation of a training induced change in one or more CMJ PRFs so that benefits derived from changes in other CMJ PRFs are not negated. Such a phenomenon may also explain, in part, some of the inaccurate CMJ PRF magnitude change predictions found in the present study.

Sub-aim ‘b’ of this study was to examine if the post-training magnitude change experienced by an individual’s CMJ PRFs following eight weeks of DJ training, could explain the post-training change in that individual’s CMJ jump height. As evident from Tables A1 to A15 (Appendix A), no consistent pattern was found between the post-training change experienced by an individual’s CMJ PRFs and that individual’s post-training jump height change. This suggests, in contrast to that suggested at the group and subgroup level, that CMJ PRFs identified in an individual level analysis may not be true CMJ PDFs. These findings may again be explained, in part, by complications arising at the individual subject level:

(a) A correlation analysis, which measures the extent to which the variance in one parameter maps the variance in another, was used to identify CMJ PRFs in the present study. In an individual level analysis however, the variance in some CMJ parameters, for certain individuals, may not be large enough to identify them as CMJ PRFs (Aragon-Vargas and Gross 1997a). Evidence of this phenomenon was found in the present study. For example, whole body concentric peak power was considered to be a likely CMJ PDF based on the group and subgroup level results, but was only identified as a CMJ PRF for two of the fifteen individuals presented (Tables A1 to A15, Appendix A). Table B1 (Appendix B) outlines the average intra-subject variation experienced by whole body peak power and, for comparative purposes, the intra-subject variation experienced by hip peak power. Peak whole body power exhibited much lower average intra-subject variability in comparison to peak hip power (3.0% compared to 8.3%), which may explain why the former was only identified as a CMJ PRF for two individuals, while the latter was identified as a CMJ PRF for nine (see Tables A1 to A15, Appendix A).

(b) Due to the multiple functional degrees of freedom of the neuromuscular system each CMJ repetition produced by an individual has the potential to have a unique pattern of movement, and as a result, CMJ parameters inherently vary from trial to trial (Bates 1996). It has been theorised that such intra-subject variability may facilitate the exploration of more optimal neuromuscular solutions for the performance of a given task (James 2004). This theory supports the identification of an individual's CMJ PRFs using intra-subject CMJ parameter variability. However, other authors have theorised that intra-subject variability in a given task's kinetics and kinematics may be as a result of the system attempting to reduce the risk of injury or attempting to stabilise important performance variables (James 2004; Latash et al. 2007). The reader is referred to section 2.4.2 for a brief discussion on the functionality of intra-subject variability. It would appear therefore that the function of intra-individual variability might not solely be to explore more optimal neuromuscular solutions for a given task. In light of this, and the fact that in some cases variability may simply be due to random movement error, there is an increased risk of finding chance correlations between certain CMJ parameters and jump height. Thus when attempting to identify an individual’s CMJ PRFs using a single subject analysis there is a risk of identifying CMJ parameters as CMJ PRFs when they actually are not.

The results of sub-aim ‘a’ and sub-aim ‘b’ (discussed above) explain why an analysis of the acute pre-training stress experienced by an individual’s CMJ PRFs may not give an insight into the effect that a given training exercise will have on that individual’s CMJ jump height (aim one). In addition, potential explanations have been provided that may explain why the outcomes of sub-aim ‘a’ and sub-aim ‘b’ (discussed above) were unique to the individual level analysis. The major implication of these findings is that the proposed pathway (Figure 2.9) may not facilitate the identification of the most effective training exercise to enhance a given individual’s CMJ jump height.

Of note, despite the findings of sub-aim ‘a’ and sub-aim ‘b’, no evidence was found to refute the suggestions made in study one of this thesis that: (a) individuals may have unique CMJ PDFs, and (b) individuals may experience a unique training stress in a given training exercise. This is based on the observation that there were no consistent trends in the post-training change data (for any of the 62 CMJ parameters calculated) that could clearly explain the inter-individual differences in CMJ jump height change. Inter-individual differences in the response to a given training intervention have also been found in previous training studies (Brown et al. 1986; Howard 1997; Lyttle 1996).

4.5 Conclusion

The current study provides evidence to support the hypothesis that an analysis of the pre-training stress that CMJ PRFs experience in a given training exercise may offer an insight into the effect that that exercise will have on a particular group’s or subgroup’s CMJ jump height. This, in conjunction with the findings of the previous study, lends support to the notion that the proposed pathway (Figure 2.9) may be able to identify the most suitable exercise to enhance a given group’s or subgroup’s CMJ jump height. However, the current study also provides evidence to suggest that the proposed pathway may not be applicable at the individual-subject level. Explanations as to why these findings were unique to the individual level of analysis were outlined, but ultimately the current method of single-subject analysis appears unable to consistently identify true CMJ PDFs or predict with a reasonable degree of accuracy the post-training change that a given CMJ PRF will experience.

Chapter 5

Study 3: A re-examination of whether a pre-training stress analysis can provide an insight into the training effect that eight weeks of drop jump training will have on countermovement jump height?

5.1 Introduction

The findings of training studies that have investigated the respective effects of drop jump, squat, jump squat and power clean training on CMJ performance outcome (i.e. jump height) are generally inconsistent (section 2.3, Tables 2.24, 2.30, 2.32 and 2.35, respectively). As a result, coaches cannot be certain as to which training exercise will be most suitable to enhance their athletes' CMJ jump height. In an attempt to address this issue a biomechanical diagnostic and prescriptive pathway has been proposed (Figure 2.9 pg77, see section 2.4 for a detailed description). Integral to the proposed pathway is the hypothesis that a pre-training stress analysis may provide an insight into the training effect that a given exercise will have on CMJ jump height. A pre-training stress analysis involves identifying the training stress experienced by CMJ performance related factors (PRFs)[1] in a given training exercise and using this information to propose the likely effects of that exercise on CMJ jump height. The group and subgroup level results of study two of this thesis suggest that a pre-training stress analysis may provide an insight into the likely effect of a given exercise on CMJ jump height, but this hypothesis was not supported at the individual subject level. It was theorised that the problems observed at the individual-subject level in study two (i.e. identified CMJ PRFs were not necessarily true CMJ PDFs and the identification of acute CMJ PRF training stress could not consistently determine post-training CMJ PRF change) may be unique to this level of analysis alone. More evidence is required to support this theory, and as such the current study will re-examine the aims of study two with a second training study. If the findings

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[1] While CMJ PDFs are those CMJ parameters that ultimately determine jump height they cannot be identified experimentally in an acute testing session, as a true cause and effect relationship cannot be established. Instead, CMJ PRFs are identified on the assumption that they are likely to be CMJ PDFs. CMJ PRFs are those CMJ parameters that are significantly correlated with CMJ jump height (see section 2.2.2 for more details).

of study two were to be supported it would suggest that the proposed pathway (Figure 2.9) may be used to identify the most effective exercise to enhance a given group's or subgroup's CMJ jump height.

A greater and more robust insight would be achieved in this study if, unlike in study two, the group and some subgroups experienced an enhancement in CMJ jump height following training. Rather than employing a different exercise in the hope that it would enhance CMJ jump height, it was decided to use a different variation of the drop jump exercise in this study. The group and subgroup level results of study two suggest that the drop jump exercise was effective in enhancing power production capacity, but that this enhanced ability may have been offset by a post-training decline in CMJ knee joint range of motion. The latter detrimental change in CMJ technique was likely brought about by repeatedly training with a training exercise (the drop jump) that employed a significantly smaller knee range of motion. In an attempt to avoid such an occurrence in this study, a drop jump exercise with a larger range of motion (about the knee and hip) will be employed. It was decided not to utilise a drop jump with a larger knee joint range of motion alone as Holcomb et al. (1996b) suggest that such a drop jump (where range of motion in one joint only is manipulated) might have a negative impact on the technique required for a successful jump. The use of two different variations of the DJ in studies two and three also allows a more direct comparison of the results of these studies, more so than if two different training exercises were utilised.

The following aim and sub-aims were investigated at a group and subgroup level:

(1) To determine whether an analysis of the acute pre- training stress experienced by CMJ PRFs in the drop jump could provide an insight into the effect that eight weeks of drop jump training will have on CMJ jump height.

Sub-aim (a): To determine if the acute pre-training training stress experienced by CMJ PRFs in the drop jump could explain the post-training magnitude change in these same CMJ PRFs following eight weeks of training.

Sub-aim (b): To determine if the post- training magnitude change experienced by CMJ PRFs following eight weeks of drop jump training could explain the post- training change in CMJ jump height.

Hypotheses:

(1) Based on the results of the pre-training stress analysis it will be possible to pre-determine the training effect that drop jump training will have on CMJ jump height.

Sub-hypothesis (a): Based on the acute pre-training stress experienced by CMJ PRFs in the drop jump it will be possible to pre-determine their post-training magnitude change.

Sub-hypothesis (b): The post-training change experienced by CMJ PRFs will ultimately determine the post-training change in CMJ jump height.

5.2 Methodology

5.2.1 Subjects

44 injury free athletic male adults (mean ± *SD*: age, 22 ± 4 years; weight 78.2 ± 9.5 kg) were recruited from students at Dublin City University. All participants were competitively active in a sport that involved a jump, and while all had previously utilised the drop jump (DJ) in previous training routines, none had undertaken structured DJ training in the previous three months. After the nature and risks of the study were explained each participant gave a written informed consent as required by the University Ethics Committee.

5.2.2 Experimental protocol

A similar experimental protocol to that utilised in study two (see section 4.2.2, pg141) was used in this study. However, as the style of DJ employed in this study is different to that used in the previous study there were some slight protocol differences. During the familiarisation session subjects were firstly asked to DJ for maximal height while minimising ground contact time (same instruction as study two). A force plate was used to measure the ground contact time of these drop jumps and each subject met the criteria for a 'bounce style DJ' that is, a DJ with a ground contact time of <200ms (Bobbert et al. 1986a). Subjects were then instructed to utilise a DJ with a larger range of motion about the hip and knee while maintaining as short a ground contact time as this form of jump would allow. As evident in Figure 5.1 these instructions clearly facilitated the production of a DJ with a greater hip and knee joint range of motion in comparison to that produced in the previous study. The concentric phase duration of the larger amplitude DJ (279ms) meets the criteria set out by Bobbert et al. (1986a) for a 'countermovement' style DJ, that is, a DJ with a concentric phase duration of greater than 260ms.

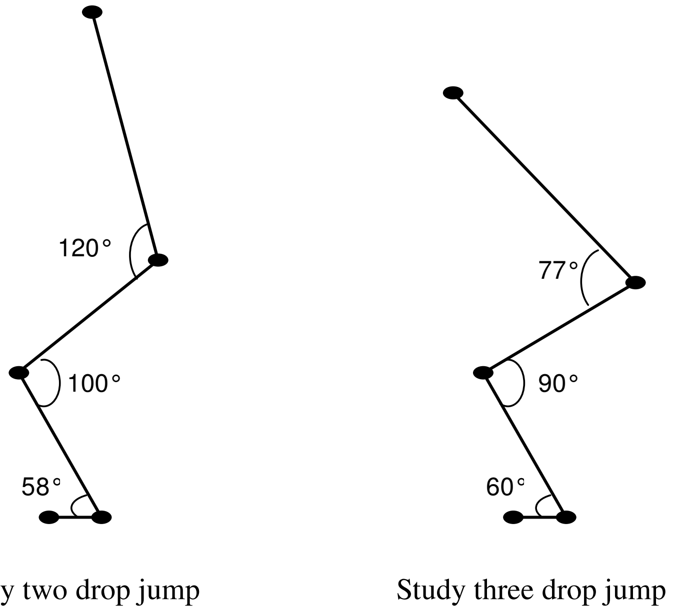

Figure 5.1 Graphical representation of the different DJ body orientations at the start of the concentric phase in DJ study two versus DJ study three.

5.2.3 Data acquisition

The method of CMJ and DJ data acquisition described in section 3.2.3, pg95 (Study 1) was used in this study.

5.2.4 Data analysis

The method of CMJ and DJ data analysis described in section 3.2.4, pg96 (Study 1) was used in this study.

5.2.5 Variables analysed

The kinetic and kinematic variables outlined in section 3.2.5, pg101 (Study 1) were also examined in this study.

5.2.6 Training Protocol

A similar training protocol to that utilised in the previous training study (section 4.2.6, pg142) was used in this study. The only difference in this study was that subjects were instructed to use a DJ with a larger hip and knee ROM (see section 5.2.2). In addition, while all 44 subjects recruited for this study underwent the eight weeks of DJ training, the control group from the previous study was used as a control for the present study.

5.2.7 Statistical analysis

Statistical analyses were run at a group and subgroup level as outlined in sections 4.2.7.1 and 4.2.7.2 (study two), respectively.

5.3 Results

This section will begin by presenting the post-training CMJ jump height change results for the training group and every individual within the training group. The results of the various analyses undertaken at the group and subgroup level will then be presented (in that order).

5.3.1 CMJ jump height change results

There was a significant increase ($p<0.05$) in CMJ jump height, pre-test versus post-test, in the training group while there was no significant change ($p>0.05$) in the control group, Table 5.1.

Table 5.1 Group level CMJ jump height changes

	n	Jump height pre (cm)	Jump height post (cm)	Percentage change	p
Training group	44	48.8 ± 5.0	51.7 ± 5.3	5.9	<0.01*
Control group	34	47.3 ± 5.8	47.2 ± 5.4	-0.2	0.7

Based on each individual's data it was observed that within the training group 29 individuals significantly ($p<0.01$) improved their CMJ jump height, fourteen had no significant change and one individual's CMJ jump height significantly reduced (Table 5.2). It is worth noting that the cluster analysis, which subgrouped individuals based on the magnitude of pre-training stress they experienced, did not place individuals in homogenous subgroups in terms of post-training jump height change.

Table 5.2 Individual level CMJ jump height changes

	Jump height pre	Jump height post (cm)	Percentage Change (cm)	p	Subgroup
Increase					
1	35.5 ± 1.5	42.3 ± 1.4	19	<0.01*	1
2	42.6 ± 1.5	49.8 ± 1.9	17	<0.01*	2
3	40.8 ± 1.5	47.2 ± 1.4	16	<0.01*	2
4	40.1 ± 0.9	46.2 ± 1.1	15	<0.01*	1
5	48.9 ± 1.3	56.0 ± 1.7	15	<0.01*	3
6	48.1 ± 1.5	54.6 ± 1.4	14	<0.01*	1
7	55.7 ± 1.3	62.7 ± 0.9	13	<0.01*	3
8	45.8 ± 1.8	50.7 ± 1.7	11	<0.01*	2
9	51.3 ± 2.4	56.9 ± 1.5	11	<0.01*	1
10	51.7 ± 1.2	57.3 ± 1.2	11	<0.01*	2
11	48.2 ± 1.3	53.2 ± 1.0	10	<0.01*	2
12	50.4 ± 0.8	55.6 ± 1.8	10	<0.01*	1
13	40.5 ± 2.2	44.9 ± 1.8	11	<0.01*	3
14	41.2 ± 1.6	45.6 ± 1.3	11	<0.01*	1
15	50.1 ± 1.5	54.7 ± 1.4	9	<0.01*	3
16	51.4 ± 1.4	55.6 ± 1.6	8	<0.01*	2
17	42.1 ± 0.8	45.3 ± 0.9	8	<0.01*	1
18	41.3 ± 1.1	44.3 ± 1.1	7	<0.01*	3
19	52.2 ± 0.7	56.1 ± 1.1	7	<0.01*	1
20	41.5 ± 1.1	44.5 ± 1.7	7	<0.01*	1
21	37.5 ± 1.4	40.1 ± 1.3	7	<0.01*	1
22	52.1 ± 1.6	55.5 ± 1.5	7	<0.01*	2
23	51.7 ± 2.1	55.4 ± 1.6	7	<0.01*	3
24	42.8 ± 2.5	45.1 ± 1.3	5	<0.01*	1
25	46.1 ± 1.9	48.8 ± 1.5	6	<0.01*	2
26	43.9 ± 1.7	46.4 ± 1.1	6	<0.01*	1
27	48.4 ± 2.0	50.3 ± 0.9	4	0.01*	3
28	49.1 ± 1.3	51.1 ± 1.7	4	0.02*	1
29	50.2 ± 1.9	52.5 ± 1.9	5	0.02*	3
No change					
1	53.4 ± 1.7	53.7 ± 1.9	1	0.58	1
2	46.9 ± 1.4	46.9 ± 1.4	0	0.95	2
3	49.8 ± 1.7	50.1 ± 1.5	1	0.66	1
4	48.6 ± 2.3	49.6 ± 2.6	2	0.11	3
5	38.7 ± 1.1	39.9 ± 1.6	3	0.05	1
6	45.2 ± 1.6	44.9 ± 2.0	-1	0.70	1
7	52.7 ± 1.9	53.5 ± 1.8	2	0.15	3
8	51.7 ± 1.5	52.6 ± 2.2	2	0.07	2
9	50.6 ± 1.3	49.3 ± 1.1	-3	0.06	3
10	47.3 ± 0.9	46.0 ± 1.9	-3	0.06	1
11	51.4 ± 1.4	51.3 ± 1.5	0	0.78	1
12	47.5 ± 1.5	48.1 ± 1.6	1	0.57	2
13	49.4 ± 1.6	49.9 ± 1.0	1	0.32	1
14	44.5 ± 1.4	45.2 ± 1.4	2	0.07	3
Decrease					
1	42.4 ± 0.9	39.4 ± 1.1	-7	<0.01*	1

* Significant difference pre versus post ($p<0.05$)

5.3.2. Group level

The primary aim of this study was to examine whether an analysis of the acute pre-training stress experienced by the group's CMJ PRFs in the DJ could give an insight into the effect that eight weeks of DJ training will have on CMJ jump height. More specifically, in light of the results presented in Table 5.1, could such an acute pre-training stress analysis have given an indication that the DJ would improve this group's CMJ jump height?

Eight CMJ parameters were significantly ($p<0.05$) correlated with CMJ jump height (Table 5.3) and were therefore deemed to be CMJ PRFs for this group (step 1, Figure 2.9).

Table 5.3 The group's CMJ PRFs

CMJ PRFs	Correlation with CMJ jump height r (p value)
1. Whole body concentric peak power	0.82 (<0.01)
2. Whole body concentric work done	0.61 (<0.01)
3. Ankle concentric peak moment	0.53 (<0.01)
4. Knee concentric peak power	0.51 (<0.01)
5. Whole body concentric rate of power development	0.46 (<0.01)
6. Ankle concentric work done	0.45 (<0.01)
7. Knee concentric rate of power development	0.43 (<0.01)
8. Whole body eccentric impulse	0.42 (<0.01)

* Significant correlation ($p<0.01$)

The acute training stress experienced by each CMJ PRF in the DJ ($DJ_{PRE} - CMJ_{PRE}$) is identified in Table 5.4 (step 2, Figure 2.9). Based on this information, it was possible to outline the likely post-training magnitude change that each CMJ PRF was expected to experience (Table 5.4, column F).

The following five CMJ PRFs were all deemed to have experienced an appropriate pre-training stress as their magnitudes were significantly greater ($p<0.05$) in the DJ in comparison to the CMJ: whole body concentric peak power, ankle concentric peak moment, whole body eccentric impulse, whole body concentric rate of power development and knee concentric rate of power development (Table 5.4). Based on the pre-training stress experienced by each of these five CMJ PRFs each was expected to enhance following training (Table 5.4, column F).

The remaining three CMJ PRFs, whole body concentric work done, knee concentric peak power and ankle concentric work done were deemed to have experienced no pre-training stress in the DJ. In light of this, none of these three CMJ PRFs were expected to experience a training induced magnitude change (Table 5.4, column F).

Table 5.4 Results of the acute pre-training stress analysis (DJ_{PRE}-CMJ_{PRE})

CMJ PRFs	A Pre CMJ (mean ± SD)	B Pre DJ (mean ± SD)	C Percentage Difference	D Significance (p)	E Acute pre-training stress	F Expected training effect
1. Whole body concentric peak power ($W. Kg^{-1}$)	49.2 ± 4.6	50.8 ± 5.5	3	<0.01*	Appropriate	Enhancement
2. Whole body concentric work done ($J.Kg^{-1}$)	7.5 ± 0.9	7.0 ± 0.8	-6	<0.01*	No stress	No change
3. Ankle concentric peak moment ($Nm.kg^{-1}$)	3.5 ± 0.4	3.9 ± 0.5	19	<0.01*	Appropriate	Enhancement
4. Knee concentric peak power ($W. Kg^{-1}$)	14.6 ± 3.3	14.8 ± 3.7	1	0.66	No stress	No change
5. Whole body concentric rate of power development ($W.kg^{-1}.s^{-1}$)	229 ± 48	310 ± 94	34	<0.01*	Appropriate	Enhancement
6. Ankle concentric work done ($J.kg^{-1}$)	2.3 ± 0.3	2.3 ± 0.3	0	0.26	No stress	No change
7. Knee concentric rate of power development ($W.kg^{-1}.s^{-1}$)	81.8 ± 28.2	96.7 ± 37.4	18	<0.01*	Appropriate	Enhancement
8. Whole body eccentric impulse ($N.kg^{-1}.s$)	2.6 ± 0.5	5.2 ± 0.3	102	<0.01*	Appropriate	Enhancement

* Significant difference CMJ pre versus DJ pre ($p<0.05$)

Sub-aim ‘a’ of this study was to determine if the acute pre-training training stress experienced by the CMJ PRFs in the DJ could explain the post-training magnitude change in these same CMJ PRFs following eight weeks of training. The post-training changes experienced by the group’s CMJ PRFs are outlined in Table 5.5. A comparison of the expected CMJ PRF post-training changes (based on the pre-training analysis) versus the actual post-training CMJ PRF changes is provided in Table 5.6. Expected post-training magnitude changes were found to be inaccurate for five of the group’s eight CMJ PRFs (Table 5.6, Column D). Ankle concentric peak moment, whole body rate of power development and knee rate of power development were all expected to enhance following training, but did not (Table 5.6). In fact, ankle concentric peak power and whole body rate of power development experienced post-training magnitude declines (Table 5.6). Neither knee concentric peak power nor ankle concentric work done were expected to enhance, based on the pre-training analysis, but the former experienced a significant enhancement while the latter experienced a significant decline (Table 5.6).

No significant correlation was found between the magnitude of pre-training stress experienced by a given CMJ PRF in the DJ ($DJ_{PRE} – CMJ_{PRE}$) and its post-training change ($CMJ_{POST} – CMJ_{PRE}$) [Table 5.7].

Table 5.5 CMJ PRF magnitude change following the eight weeks of drop jump training

CMJ PRFs	Pre CMJ (mean ± SD)	Post CMJ (mean ± SD)	Percentage Difference	Post-training change
1. Whole body concentric peak power (W. Kg^{-1})	49 ± 4	51 ± 5 *	4	Enhancement
2. Whole body concentric work done (J.Kg^{-1})	7.5 ± 0.7	7.9 ± 0.8	5	No change
3. Ankle concentric peak moment (Nm.kg^{-1})	3.4 ± 0.4	2.9 ± 0.3 *	-15	Decline
4. Knee concentric peak power (W. Kg^{-1})	14.6 ± 3	18.4 ± 3.2 *	26	Enhancement
5. Whole body concentric rate of power development (W.kg^{-1}.s^{-1})	229 ± 48	213 ± 44 *	-7	Decline
6. Ankle concentric work done (J.kg^{-1})	2.3 ± 0.3	2 ± 0.3 *	-13	Decline
7. Knee concentric rate of power development (W.kg^{-1}.s^{-1})	77 ± 23	84 ± 29	9	No change
8. Whole body eccentric impulse (N.kg^{-1}.s)	2.5 ± 0.4	3 ± 0.5 *	20	Enhancement

* Significant within group (pre vs. post) and between group (training vs. control) change ($p<0.05$)

Table 5.6 A comparison of expected versus actual CMJ PRF post-training magnitude changes

CMJ PRFs	A Pre-training Stress	B Expected training effect	C Actual training effect	D Accuracy of expected training effect
1. Whole body concentric peak power	Appropriate	Enhancement	Enhancement	Accurate
2. Whole body concentric work done	No stress	No change	No change	Accurate
3. Ankle concentric peak moment	Appropriate	Enhancement	Decline	Inaccurate
4. Knee concentric peak power	No stress	No change	Enhancement	Inaccurate
5. Whole body concentric rate of power development	Appropriate	Enhancement	Decline	Inaccurate
6. Ankle concentric work done	No stress	No change	Decline	Inaccurate
7. Knee concentric rate of power development	Appropriate	Enhancement	No change	Inaccurate
8. Whole body eccentric impulse	Appropriate	Enhancement	Enhancement	Accurate

Table 5.7 Correlation (r) between the acute-pre training stress experienced by a CMJ PRF (DJ_{PRE}-CMJ_{PRE}) and its post training change ($CMJ_{POST} - CMJ_{PRE}$)

CMJ PRFs	r	p
1. Whole body concentric peak power	0.18	0.24
2. Whole body concentric work done	0.29	0.06
3. Ankle concentric peak moment	-0.29	0.06
4. Knee concentric peak power	0.23	0.13
5. Whole body concentric rate of power development	0.08	0.64
6. Ankle concentric work done	0.00	0.98
7. Knee concentric rate of power development	0.03	0.87
8. Whole body eccentric impulse	0.12	0.44

Sub-aim ‘b’ of this study was to examine if the post-training magnitude changes experienced by the group’s CMJ PRFs following eight weeks of DJ training could explain the post-training change in the group’s CMJ jump height. More specifically, could the post-training changes experienced by the CMJ PRFs explain the increase in the group’s mean CMJ jump height? The post-training change experienced by each of the group’s CMJ PRFs has already been presented in Table 5.5. Three of the eight CMJ PRFs experienced an enhancement, three others declined while the remaining two experienced no-post-training change (Table 5.5).

The correlations between the post-training change in CMJ jump height and the post-training magnitude change in each of the eight CMJ PRFs are presented in Table 5.8. A significant positive correlation was found between the post-training training change in CMJ jump height and the post-training change in both whole body concentric peak power and whole body concentric work done, respectively (Table 5.8, Figures 5.2 and 5.3).

Table 5.8 Correlation (r) between the post-training change in a CMJ PRF ($CMJ_{POST} - CMJ_{PRE}$) and the post training change in CMJ jump height ($CMJ_{POST} - CMJ_{PRE}$)

CMJ PRFs	r	Significance (p)
1. Whole body concentric peak power	0.56 *	<0.01
2. Whole body concentric work done	0.59 *	<0.01
3. Ankle concentric peak moment	0.04	0.26
4. Knee concentric peak power	0.26	0.13
5. Whole body concentric rate of power development	-0.07	0.66
6. Ankle concentric work done	0.04	0.82
7. Knee concentric rate of power development	0.03	0.20
8. Whole body eccentric impulse	0.00	0.99

* Significant correlation ($p<0.05$)

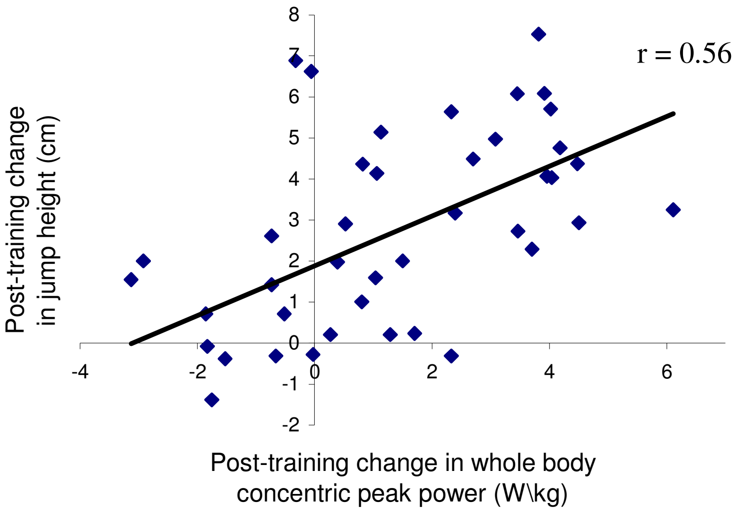

Figure 5.2 Scatter plot of the relationship between the post-training change in whole body concentric peak power and the post-training change in CMJ jump height

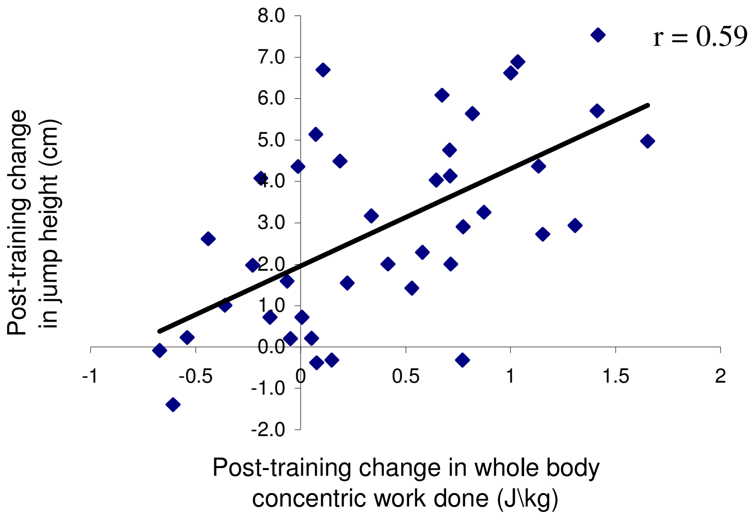

Figure 5.3 Scatter plot of the relationship between the post-training change in whole body concentric work done and the post-training change in CMJ jump height

5.3.3 Subgroup level

Individuals were initially subgrouped based on the magnitude of pre-training stress they experienced in the DJ. Six CMJ parameters were used in the cluster analysis (Table 5.9). Two parameters, whole body rate of power development and knee rate of power development were excluded from the analysis as the former was highly correlated with whole body peak power (r = 0.70) while the latter was highly correlated with knee peak power (r = 0.70).

A relatively large increase in the agglomeration coefficient occurred between the three subgroup and two subgroup solutions (23% increase) [Table 5.10], indicating that a three-cluster solution was appropriate. The dendrogram produced by the cluster analysis is provided in Figure 5.4. Solution validity was examined by checking for between subgroup differences in the magnitude of pre-training stress which was confirmed with a significant MANOVA Wilks' $\gamma = 0.07$, $p<0.001$.

Table 5.9 CMJ parameters used in the cluster analysis

CMJ parameters
1. Whole body concentric peak power
2. Whole body concentric work done
3. Ankle concentric peak moment
4. Knee concentric peak power
5. Ankle concentric work done
6. Whole body eccentric impulse

Table 5.10 Change in the agglomeration coefficient as the number of subgroups changed

Change in number of subgroups	Agglomeration coefficient	Percentage change in agglomeration coefficient
7 to 6	112.0	14
6 to 5	126.0	13
5 to 4	143.4	14
4 to 3	161.9	13
3 to 2	198.9	23
2 to 1	252.0	27

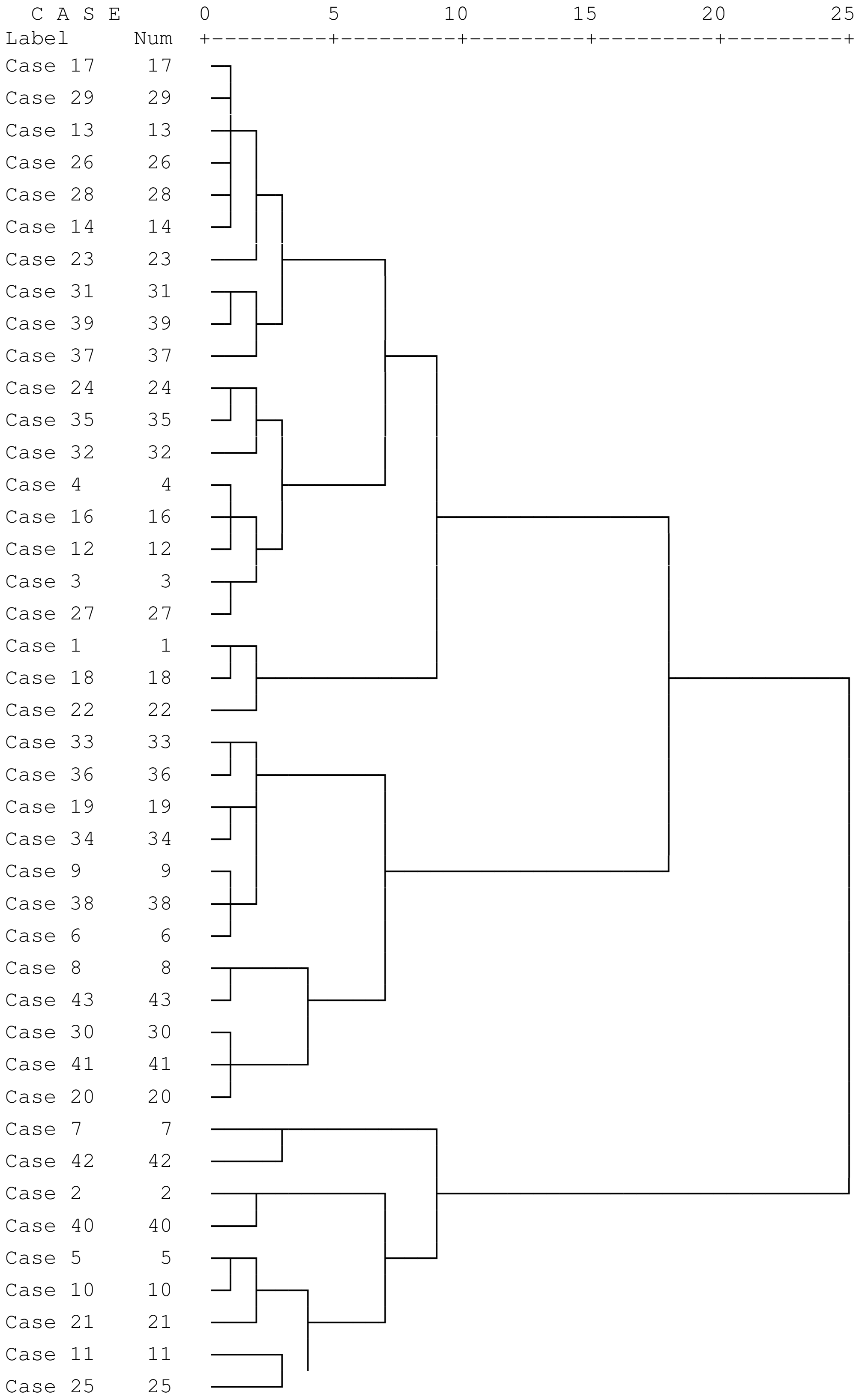

Figure 5.4 Dendrogram produced in the Ward’s method hierarchal cluster analysis

The three subgroups created each experienced a post-training increase in CMJ jump height (Table 5.11). In light of these findings, the primary aim of this study was to examine whether the acute pre-training stress experienced by each respective subgroup could have given an indication that the DJ would improve each subgroups CMJ jump height?

Table 5.11 Subgroup mean change (± SD) in CMJ jump height pre to post-training

	Change in CMJ height (cm) $[CMJ_{POST} - CMJ_{PRE}]$
Subgroup 1	3.1 ± 2.6 *
Subgroup 2	2.8 ± 2.2 *
Subgroup 3	2.2 ± 2.7 *
Between subgroup differences	No

Between subgroup differences in the magnitude of pre-training stress (DJ_{PRE} - CMJ_{PRE}) experienced by CMJ PRFs in the DJ are outlined in Table 5.12. Table 5.12 also details the actual pre-training stress (appropriate, inappropriate or no training stress) experienced by the CMJ PRFs in each subgroup. Based on this latter information it was possible to outline the likely post-training magnitude change that each CMJ PRF was expected to experience (in each subgroup) following training (Table 5.13). While numerous between subgroup differences were evident in the magnitude of pre-training stress experienced (DJ_{PRE} - CMJ_{PRE}), the actual pre-training stress experienced by CMJ PRFs (appropriate, inappropriate or no training stress) was subject to much less between subgroup variation. That is, while individuals were successfully subgrouped into homogenous subgroups based on the magnitude of training stress they experienced, each subgroup experienced a similar form of pre-training stress (i.e. appropriate, inappropriate or no training stress). For example, whole body concentric work done, knee concentric peak power and ankle concentric work done did not experience a pre-training stress in each subgroup, while ankle concentric peak moment and ankle eccentric peak impulse experienced an appropriate pre-training stress in each subgroup (Table 5.13). In light of the between subgroup similarities in the nature of the pre-training stress experienced, the expected post-training CMJ PRF changes were quite similar across subgroups. For example, each subgroup was expected to experience an increase in at least two CMJ PRFs and no change in three CMJ PRFs (Table 5.14).

Sub-aim ‘a’ of this study was to determine if the acute pre-training training stress experienced by the CMJ PRFs in the DJ could explain the post-training magnitude changes in these same CMJ PRFs following eight weeks of training. Similar to that found at the group level, expected post-training CMJ PRF changes (Table 5.13) often did not subsequently occur for each subgroup (Table 5.14). For example, whole body concentric work done was not expected to change following training in each subgroup (Table 5.13), but subgroups one and two experienced a post-training enhancement in this same CMJ PRF (Table 5.14). Additionally, despite numerous between subgroup differences in the magnitude of pre-training stress experienced by the CMJ PRFs in the DJ (Table 5.13), there were no between subgroup differences in post-training CMJ PRF magnitude changes (Table 5.14).

Table 5.12 The magnitude of pre-training stress (DJ_{PRE} - CMJ_{PRE}) experienced by each subgroup in the drop jump

	Whole body concentric peak power (W. Kg^{-1})	Whole body concentric work done ($J.Kg^{-1}$)	Ankle concentric peak moment ($Nm.kg^{-1}$)	Knee concentric peak power (W. Kg^{-1})	Ankle concentric work done ($J.kg^{-1}$)	Whole body eccentric impulse ($N.kg^{-1}.s$)
Subgroup 1 (n = 21)	1.7 ± 1.7 Appropriate stress *	-0.5 ± 0.5 No stress *	0.4 ± 0.2 Appropriate stress *	0.0 ± 1.8 No stress	0.0 ± 0.2 No stress	2.3 ± 0.3 Appropriate stress *
Subgroup 2 (n = 11)	3.6 ± 3.4 Appropriate stress *	-0.8 ± 0.7 No stress *	1.2 ± 0.2 Appropriate stress *	0.7 ± 3.0 No stress	0.5 ± 0.2 No stress	2.7 ± 0.3 Appropriate stress *
Subgroup 3 (n = 12)	-1.2 ± 2.1 No stress	-0.2 ± 0.6 No stress	0.6 ± 0.2 Appropriate stress *	-0.8 ± 1.6 No stress	-0.1 ± 0.2 No stress	3.1 ± 0.1 Appropriate stress *
Between subgroup stress differences ($p < 0.05$)	2,1 > 3	None	2 > 1,3	None	2 > 1,3	3 > 2 > 1

* Significant difference DJ magnitude vs. CMJ magnitude ($p<0.05$)

Table 5.13 The CMJ PRF magnitude changes that each subgroup was expected to experience following the training period

	Whole body concentric peak power (W. Kg^{-1})	Whole body concentric work done ($J.Kg^{-1}$)	Ankle concentric peak moment ($Nm.kg^{-1}$)	Knee concentric peak power (W. Kg^{-1})	Ankle concentric work done ($J.kg^{-1}$)	Whole body eccentric impulse ($N.kg^{-1}.s$)
Subgroup 1	Enhance	No change	Enhance	No change	No change	Enhance [1]
Subgroup 2	Enhance	No change	Enhance	No change	No change	Enhance [1]
Subgroup 3	No change	No change	Enhance	No change	No change	Enhance [1]

[1] Subgroup 3 enhancement > Subgroup 2 enhancement > Subgroup 1 enhancement

Sub-aim ‘b’ of this study was to examine whether the post-training magnitude changes experienced by the CMJ PRFs in a particular subgroup could explain the subgroup’s post-training change in CMJ jump height. Similar to that found at the group level, each subgroup exhibited both CMJ PRF enhancements and declines (Table 5.14).

Table 5.14 The actual CMJ PRF post-training magnitude changes (CMJ_{POST} - CMJ_{PRE}) experienced by each subgroup

	Whole body concentric peak power ($W. Kg^{-1}$)	Whole body concentric work done ($J.Kg^{-1}$)	Ankle concentric peak moment ($Nm.kg^{-1}$)	Knee concentric peak power ($W. Kg^{-1}$)	Ankle concentric work done ($J.kg^{-1}$)	Whole body eccentric impulse ($N.kg^{-1}.s$)
Subgroup 1 (n = 21)	2.0 ± 2.4 Enhancement *	0.5 ± 0.7 Enhancement *	-0.5 ± 0.3 Decline *	3.3 ± 2.8 Enhancement *	-0.2 ± 0.1 Decline *	0.4 ± 0.4 Enhancement
Subgroup 2 (n = 11)	0.9 ± 2.9 No change	0.5 ± 0.6 Enhancement *	-0.5 ± 0.2 Decline *	3.1 ± 2.9 Enhancement *	-0.4 ± 0.2 Decline *	0.5 ± 0.6 Enhancement
Subgroup 3 (n = 12)	0.9 ± 2.0 No change	0.2 ± 0.7 No change	-0.5 ± 0.2 Decline *	4.0 ± 2.2 Enhancement *	-0.3 ± 0.3 Decline *	0.6 ± 0.8 Enhancement
Between subgroup differences ($p < 0.05$)	None	None	None	None	None	None

* Significant within group post-training change ($p<0.05$)

5.4 Discussion

5.4.1 Group level

In the current study eight weeks of DJ training improved the group's mean CMJ jump height (see Table 5.1). In light of this the primary aim of this study became: could an analysis of the acute pre-training stress experienced by the group's CMJ PRFs in the DJ have given an indication that the DJ would improve this group's CMJ jump height? Based on the acute pre-training stress analysis (Table 5.4) five CMJ PRFs were expected to enhance following training, while three CMJ PRFs were not expected to change. While this alone would suggest that the pre-training stress analysis could have predicted that the DJ would improve this group's CMJ jump height, this was only a chance finding as the respective hypotheses concerning sub-aim 'a' and sub-aim 'b' (which form the basis of the pre-training stress analysis) were not supported (see below).

Sub-aim 'a' examined whether the acute pre-training training stress experienced by CMJ PRFs in the DJ could explain the post-training magnitude change in these same CMJ PRFs. Of the eight expected post-training CMJ PRF changes proposed in the current study five were subsequently found to be inaccurate (Table 5.6). This is in contrast to what was found at the group level in the previous study, where the majority of the proposed post-training CMJ PRF changes were found to be accurate (Table 4.6, pg153). Inaccurate post-training change predictions were common at the individual subject level in the previous study (Tables A1-A15, Appendix A) but it was theorised that this was due to complications arising at the individual subject level alone. The results of the current study clearly refute this notion. In addition, the results of the current study do not support the supposition of Bobbert et al. (1986a) that identifying the pre-training stress experienced by a given CMJ PRF provides an insight into its likely post-training change. Possible explanations for each of the unexpected post-training CMJ PRF changes found in this study are outlined below.

Whole body rate of power development experienced an appropriate pre-training stress in the DJ but actually declined following training (Table 5.6). This unexpected finding may be as a result of the observed 8% increase ($p<0.05$) in concentric phase duration following training (Table C1, Appendix C). An increase in concentric phase duration is likely to result in an increase in the time between the start of the concentric phase and the time of peak power, which may explain the reduction in whole body rate of power development. Indeed, a significant negative correlation ($r = -0.79$, $p<0.05$) between the post-training change in concentric phase duration and the post-training change in whole body rate of power development supports this theory. The post-training increase in the duration of the concentric phase may also explain the unexpected lack of enhancement in knee rate of power development following training (Table 5.6). A significant increase in knee concentric peak power (Table 5.5), which would have been expected to increase knee rate of power development, appears to have been offset by the significant increase in the duration of the concentric phase (Table C1, Appendix C). Indeed a significant negative correlation ($r = -0.53$, $p<0.05$) between the post-training change in concentric phase duration and the post-training change in knee rate of power development supports this hypothesis.

Knee concentric peak power increased significantly following training (Table 5.5) despite not having experienced an appropriate pre-training stress in the DJ (Table 5.4). The increase in knee concentric power may, however, have derived from an enhanced ability to utilise the stretch shortening cycle (see section 2.2.7 for more details) at the knee. While not identified as CMJ PRFs in the pre-training analysis, both knee moment at joint reversal and eccentric vertical velocity experienced an appropriate pre-training stress in the DJ and increased significantly following training ($p<0.05$) [Table C1, Appendix C]. An increase in such parameters, that is, a faster pre- stretch and larger force at the end of the stretch, has the potential to augment the mechanical output of the subsequent concentric phase (Bobbert et al. 1996; Bosco et al. 1981).

Ankle concentric peak moment and ankle concentric work done reduced significantly following training ($p<0.05$) [Table 5.5]. These unexpected post-training changes appear to be as a result of the ankle joint contributing less actively (more passively) to propulsion following the training period. This is further evidenced by the fact that other kinetic based ankle parameters such as ankle peak power and ankle rate of power development also decreased significantly following training ($p<0.05$) [Table C1, Appendix C]. In addition, these post-training kinetic changes occurred without any notable change in ankle joint range of motion (Table C1, Appendix C). A possible explanation for these findings is that the knee joint became a more active contributor to propulsion following training. A greater neuromuscular output about the knee (which was evidenced in this study) would result in a greater inertia of the body's centre of mass, which may in effect have pulled the ankle joint into plantar flexion and resulted in a reduced neuromuscular output about the ankle. This is in accordance with the inter-segmental biomechanical constraint which states that a muscular action at one joint can act to accelerate another joint it does not span due to inertial forces being transmitted from one segment to another (inertial coupling) [Zajac 1993]. The proposal that the knee became a more active contributor to propulsion following training is supported by significant post-training increases ($p<0.05$) in knee concentric peak power (Table 5.5), knee concentric peak moment and knee concentric work done [Table C1, Appendix C].

In light of the explanations outlined above regarding the unexpected CMJ PRF post-training changes, it appears that the post-training change experienced by a given CMJ parameter can be heavily influenced by the post-training change experienced by other CMJ parameters. This is in accordance with the notion that most CMJ parameters proposed as relevant to CMJ jump height are interrelated in a complex fashion (Aragon-Vargas and Gross 1997b). It appears unlikely therefore that one will be able to consistently identify the post-training change that a given CMJ PRF will experience based on the pre-training stress that that same CMJ PRF experienced.

It is difficult to explain why some of the parameters that appeared to be influencing the CMJ PRF post-training magnitude changes (see above), were not themselves identified as CMJ PRFs in the pre-training analysis. Perhaps they had only relatively weak relationships with CMJ jump height prior training but due to notable training induced changes they had a greater influence over jump height following training.

A second underlying assumption of the pre-training stress analysis is that the post-training change experienced by the CMJ PRFs will ultimately determine the post-training change in CMJ jump height (Sub-aim b). In other words, can the identified CMJ PRFs be considered to be true CMJ PDFs? This was investigated in two ways: (a) by examining whether the cumulative post-training changes experienced by the group's CMJ PRFs could explain the post-training change in CMJ jump height (Table 5.5), and (b) by correlating the post-training magnitude change of each CMJ PRF with the magnitude of CMJ jump height change (Table 5.8).

As outlined in Table 5.5, three CMJ PRFs enhanced following training, another three declined and the remaining two did not experience a post-training magnitude change. Given that the group significantly increased their CMJ jump height following training (Table 5.1) one would have expected the majority of CMJ PRFs to have enhanced and certainly not have expected three CMJ PRFs to have experienced a decline. These findings therefore suggest that some of the CMJ PRFs identified in the pre-training analysis were not true CMJ PDFs. To further investigate this issue the magnitude of CMJ PRF change and the magnitude of jump height change were examined for correlations. Only two of the eight CMJ PRFs, whole body concentric peak power and whole body concentric work done, were correlated with jump height and could thus be considered true CMJ PDFs (Table 5.8). The results of this study demonstrate that identifying CMJ PRFs from a single time point, as is the norm (e.g. Dowling and Vamos 1993; Harman et al. 1990), does not necessarily identify true CMJ PDFs. This illustrates the need to utilise training interventions to improve the efficacy of CMJ PDF identification (Sheppard et al. 2009).

So why were the CMJ PRFs identified at the group level in the current study not true CMJ PDFs? This appears to be due to the fact that correlation does not imply causation. Some parameters (e.g. ankle peak moment) may simply have been identified as CMJ PRFs by virtue of their contributory relationship to likely CMJ PDFs (e.g. whole body peak power). In addition, other parameters (e.g. whole body rate of power development) may have been identified as CMJ PRFs as a result of the large influence that likely CMJ PDFs (e.g. whole body peak power) have on them.

In summary, the group level results of the current study showed that: (a) identifying the pre-training stress experienced by a CMJ PRF could not consistently give an insight into that CMJ PRFs post-training change, and (b) CMJ PRFs identified using a correlation analysis were not necessarily true CMJ PDFs. These findings refute the theory proposed in study two of this thesis and by Bobbert et al. (1987a) that a pre-training stress analysis can provide an insight into the effect that a given training exercise will have on a group's CMJ jump height. As such the findings of the current study do not support the use of the proposed biomechanical diagnostic and prescriptive pathway in identifying the most effective exercise to enhance a given group's CMJ jump height.

Another pertinent question, that has yet to be answered, is how did the group's mean CMJ jump height improve? To answer this question it is necessary to firstly identify all the likely CMJ PDFs and secondly examine their post-training changes. To facilitate the identification of likely CMJ PDFs the post-training change in CMJ jump height change was correlated with the post-training change experienced by each of the CMJ parameters calculated in this study (see section 3.2.5). Four additional significant correlations (other than the two found previously, see above) were found: hip concentric peak power, amplitude of the centre of mass, whole body eccentric work done and hip concentric work done (Table C2, Appendix C). This brings to six the total number of CMJ parameters identified as likely CMJ PDFs based on a post-training correlation analysis (Table C2, Appendix C). The group level post-training changes experienced by the six likely CMJ PDFs are presented in Table C3 (Appendix C). Whole body concentric peak power, amplitude of the centre of mass and whole body eccentric work done all increased significantly following training ($p<0.05$), while the remaining three parameters did not experience a significant post-training change. As such, these findings appear to explain the statistically significant ($p<0.05$), yet moderate (effect size = 0.6), increase in mean CMJ jump height observed in the current study.

Interestingly, the larger amplitude DJ utilised in this study resulted in a post-training CMJ technique enhancement (increased COM amplitude) that complimented the post-training enhancement in power production capacity. This is in contrast to what was observed for the smaller amplitude DJ utilised in study two of this thesis, where it was suggested that a training induced technique change (decline in knee joint range of motion) appeared to offset the increased power production capacity. It could be theorised, therefore, that the DJ utilised in the current study exhibited a greater training specificity to the CMJ than the DJ utilised in the previous study, and as such, facilitated a greater increase in CMJ jump height. This suggestion is consistent with the findings of Young et al. (1995) who found a strong relationship between jump height in a CMJ and jump height in a larger amplitude DJ ($r = 0.98$) but no correlation ($r = 0.37$) between jump height in a CMJ and jump height in a low amplitude DJ. The findings of both the current study and Young et al. (1995) lend support to the theory that a short contact time (small amplitude of movement) in the DJ is less important when training for the CMJ as opposed to training for a jump (e.g. high jump takeoff) where propulsion time is more restricted (Young et al. 1995). In contrast to the current study, Young et al. (1999) found that training with a relatively large amplitude DJ did not increase CMJ jump height. This disparity may be due to the longer duration of the current study (eight weeks compared to six weeks) and\or the fact that different groups may have different CMJ PDFs (e.g. time between peak power and take-off was considered a likely CMJ PDF for the training group utilised in study two but was not considered to be a likely CMJ PDF in study three). Unfortunately, Young et al. (1999), as with most studies, do not provide data on how joint and whole body kinetics and kinematics changed with training (if at all).

5.4.2 Subgroup level

The outcomes of the subgroup level results are no different to those discussed above at the group level. The hypothesis that a pre-training analysis of the training stress experienced by the CMJ PRFs in each subgroup may give an insight into each subgroup's post-training CMJ jump height change was not supported. This, as at the group level, was due to the inability to identify true CMJ PDFs (sub-hypothesis 'a' disproved) and the inability to consistently predict the post-training change that a given CMJ PRF will experience following training (sub-hypothesis 'b' disproved). The reasons proposed above (group level discussion) as to why sub-hypothesis 'a' and sub-hypothesis 'b' were disproved are equally applicable here. In light of all of this, the findings of the current study do not support the use of the proposed biomechanical diagnostic and prescriptive pathway (Figure 2.9) to identify the most effective exercise to enhance a given subgroup's CMJ jump height.

5.5 Conclusion

The results of the current study suggest that the proposed pre-training stress analysis will not be able to provide an insight into the effect that a particular exercise will have on a given group's or subgroup's CMJ jump height. This is based on the fact that (a) CMJ PRFs are not necessarily true CMJ PDFs, and (b) the identification of the acute pre-training stress experienced by a CMJ PRF does not necessarily give an insight into the post-training change that that CMJ PRF will undergo. Therefore, the findings of the current study do not support the use of the proposed biomechanical diagnostic and prescriptive pathway to identify the most effective exercise to enhance a given group's or subgroup's CMJ jump height.

Chapter 6

Summary, conclusion, limitations and directions for future research

6.1 Summary

Countermovement jump (CMJ) ability is an important contributor to successful performance in many sports, including volleyball and basketball (Harman et al. 1990; Rosenstein et al. 2002). While the drop jump, squat, jump squat and power clean training exercises are each purported to enhance maximal CMJ jump height, there are generally inconsistent findings regarding their effectiveness at doing so (section 2.3, Tables 2.24, 2.30, 2.32 and 2.35, respectively). In addition, there is no overwhelming evidence to suggest that between study differences in subject characteristics, training intensity, frequency or volume can fully explain the inconsistent training outcomes of a given training exercise (section 2.3, Tables 2.24, 2.30, 2.32 and 2.35, respectively). All of this points to the fact that a particular training exercise may be more suited to some individuals than others, which may be explained (in part) by: (a) different individuals having different CMJ performance determining factors (PDFs), and\or (b) different individuals experiencing different training stresses in a given training exercise. Indeed, study one provided evidence that supports both ‘a’ and ‘b’ by showing that different individuals have the capacity to possess unique CMJ performance related factors (PRFs)[1] [Tables 3.5-3.10] and experience different acute training stresses in a given training exercise (Table 3.11).

In an attempt to identify the most effective exercise to enhance athletes’ CMJ jump height, a biomechanical diagnostic and prescriptive pathway was proposed (Figure 2.9 pg77, see section 2.4 for a detailed description). It was hoped that this pathway would allow the identification of the most effective exercise to enhance a given group’s, subgroup’s or individual’s CMJ jump height, and thus facilitate

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[1] While CMJ PDFs are those CMJ parameters that ultimately determine jump height they cannot be identified experimentally in an acute testing session, as a true cause and effect relationship cannot be established. Instead, CMJ PRFs are identified on the assumption that they are likely to be CMJ PDFs. CMJ PRFs are those CMJ parameters that are significantly correlated with CMJ jump height (see section 2.2.2 for more details).

more effectual and efficient training. Of note, the proposed pathway takes into account that different individuals (and thus groups) have unique CMJ PRFs (point ‘a’ above) and may experience a different training stress in a given training exercise (points ‘b’ above). Study one showed that the proposed pathway may have, theoretically at least, facilitated the identification of the most effective exercise for a given group, subgroup or individual. This however was based on the premise that a pre-training stress analysis, which is integral to the proposed pathway, can provide a pre-training insight into the effect that a given training exercise will have on CMJ jump height. A pre-training stress analysis involves identifying (using statistical relationships and tests of mean difference) the acute training stress experienced by CMJ PRFs in a given training exercise (see section 2.4 for more details). The hypothesis that such an analysis could provide an insight into the effect of a particular training exercise (drop jump) on CMJ jump height was examined using drop jump training interventions (studies two and three).

The results of study two showed that the pre-training stress analysis may have given an indication that the drop jump would not improve the group’s, or each subgroup’s, CMJ jump height. The same could not be said however at the individual subject level, as it was found that: (i) identified CMJ PRFs were not necessarily true CMJ PDFs, and (ii) the pre-training stress experienced by CMJ PRFs did not provide a consistent insight into their respective post-training changes. It was proposed that phenomena ‘i’ and ‘ii’ may have arisen due to certain complexities that are only present at the individual subject level (see section 4.4.3 for more details). Study three, however, subsequently disproved this theory by clearly showing that both ‘i’ and ‘ii’ (above) can also occur at the group and subgroup level. It appears that CMJ PRFs may not be true CMJ PDFs because correlation does not necessarily imply causation (Sheppard 2009). In addition, it appears that the pre-training stress experienced by a CMJ PRF may not give an insight into a CMJ PRFs post-training change due to the complex inter-related nature of numerous CMJ parameters (Aragon-Vargas and Gross 1997b).

6.2 Conclusion

A review of literature indicated the need for researchers to develop a means of identifying, prior to training, the most effective exercise to enhance athletes' CMJ jump height. In light of this a biomechanical diagnostic and prescriptive pathway was proposed (Figure 2.9). Central to the proposed pathway was the theory that an analysis of the acute pre-training stress that CMJ PRFs experience in a given training exercise (pre-training analysis) will provide an insight into the effect that that an exercise will have on CMJ jump height (Bobbert et al. 1987a). However, the combined results of studies two and three did not support this hypothesis. As such the use of the proposed pathway (Figure 2.9) to identify the most effective exercise to enhance a given group's, subgroup's or individual's CMJ jump height cannot be supported.

6.3 Limitations

While explanations as to why the proposed pathway was ultimately found to be ineffectual have already been outlined (see section 5.4, study 3) limitations in how the pathway was actually assessed may also be partly responsible and should be acknowledged. Firstly, the current study used discrete measures to represent neuromuscular capacity\output (e.g. peak power) rather than using continuous measures (e.g. through the use of a phase plane analysis). Secondly, in the current study a kinetic CMJ parameter was deemed to be appropriately stressed when that parameter's magnitude was significantly greater in a training exercise than in the CMJ. However, a given parameter's magnitude in the CMJ may not be an accurate reflection of maximal neuromuscular capacity but instead a reflection of the neuromuscular output utilised while jumping. Thus while a given parameter's magnitude may be greater in a training exercise, this may not necessarily imply that the underlying neuromuscular capacity is being stressed. Finally, the presence or absence of acute training stress in the current study was only quantified at the start of the training period and it was assumed that this did not change during the training period.

6.4 Directions for future research

A better understanding of the kinetic and kinematic parameters that determine performance outcome in a given task (PDFs) should lead to the development of more effective and efficient training programs (Hori et al. 2009; Davis et al. 2003). Researchers typically identify potential PDFs using a correlation analysis and data obtained in an acute testing session (Sheppard et al. 2009). However, such an analysis only identifies an association between performance outcome and a given kinetic or kinematic parameter, it does not indicate cause and effect. A better insight into the PDFs of a given task can be achieved with the use of a training intervention. Here the post-training change in performance outcome can be correlated with the post-training change in the kinetic and kinematic parameters of interest. The current study highlighted the weakness of relying on acute testing sessions for the identification of potential PDFs. It was clearly shown, at both a group and individual level of analysis, that CMJ performance related factors were not necessarily true CMJ PDFs. In light of this, it is recommended that future studies, which aim to identify the potential PDFs of a given task, should attempt to do so using training intervention studies rather than acute testing sessions. Clearly the disadvantage of such an approach is that a pre-training insight into the true PDFs of a given task is not possible. Researchers should thus examine the generalisability of PDFs. For example, if it was found that hip peak power was consistently a CMJ PDF across a number of different studies, a coach can be reasonably confident that hip peak power is likely to be a CMJ PDF for his group of athletes.

Further training intervention studies could examine whether the group level CMJ PDFs identified in both studies two and three of the current thesis are also evident in different training groups, thereby examining the extent to which the identified PDFs can be generalised.

An understanding of the neuromuscular capacities that are stressed (overloaded) in a given training exercise should also allow for the development of more effective and efficient training programs. Previous authors have attempted to establish the training stress imposed by a given training exercise by comparing the magnitude of kinetic parameters produced in the training exercise with those produced in the task being trained (Bobbert et al. 1986a; Bobbert et al. 1987a and b; Holcomb et al. 1996a). However, the results of such an acute training stress analysis, which are based purely on statistical difference, does not imply cause and effect. A better understanding of the training stress imposed by a given training exercise can be obtained from training intervention studies. Here, training induced changes in kinetic parameters can provide an insight into the neuromuscular capacities that were stressed during training. The current study found, at both a group and individual subject level, that an acute pre-training stress analysis could not provide a reliable insight into the post-training change that a given CMJ parameter would experience. As a result of this, it is recommended that future studies, that aim to establish the training stress imposed on the neuromuscular system by a given training exercise, should attempt to do so using training intervention studies rather than acute testing sessions.

It is widely accepted that the performance outcome of a given task is, in part, influenced by the technique employed (Lees 2000). It is surprising therefore that very few training studies have quantified the effect of a particular training exercise on the technique employed in a given task (Hunter and Marshall 2002). The current study found that a training exercise (the drop jump) could induce post-training technique changes in a given task (the CMJ). Moreover, the current study also found that training induced technique changes may well influence the overall outcome of a training intervention. For example, study two found that a period of low amplitude drop jump training induced a post-training reduction in CMJ knee joint range of motion, which may have prevented an increase in CMJ jump height following training. In contrast, study three found a period of larger amplitude (about the knee and hip) drop jump training induced a post-training enhancement in the amplitude of the COM, which may have facilitated an increase in CMJ jump height. There is a clear need for future training studies to examine the effects of various training exercises on the technique employed in specific sporting tasks. Such studies should also look to explain the reasons behind training induced technique changes.

Bibliography

Adams, K., O'Shea, J. P., O'Shea, K. L. and Climstein, M. 1992. The effect of six weeks of squat, plyometric and squat-plyometric training on power production. *Journal of Applied Sport Science Research*. 6 (1), pp36-41.

Alemany, J. A., Pandorf, C. E., Montain, S. J., Castellani, J. W., Tuckow, A. P. and Nindl, B. C. 2005. Reliability assesment of ballistic jump squats and bench throws. *Journal of Strength and Conditioning Research*. 19 (1), pp33-38.

Aragon-Vargas, L. F. and Gross, M. M. 1997a. Kinesiological factors in vertical jump performance: differences within individuals. *Journal of Applied Biomechanics*. 13 (1), pp45-65.

Aragon-Vargas, L. F. and Gross, M. M. 1997b. Kinesiological factors in vertical jump performance: differences among individuals. *Journal of Applied Biomechanics*. 13 (1). 24-44.

Asmussen, E. and Bonde-Petersen, F. 1974. Storage of elastic energy in skeletal muscles in man. *Acta Physiologica Scandinavica*. 91 (3), pp385-392.

Baechle, T. R., Earle, R. W. and Wathen, D. 2000. Resistance training *IN*: Baechle, T.R. and Earle, R.W (eds.). *Essentials of Strengh Training and Conditioning*. Second edition. Leeds, U.K. Human Kinetics.

Baker, D., Nance, S. and Moore, M. 2001. The load that maximizes the average mechanical power output during jump squats in power-trained athletes. *Journal of Strength and Conditioning Research*. 15 (1), pp92-97.

Baker, D. 1996. Improving vertical jump performance through general, special, and specific strength training: a brief review. *Journal of Strength and Conditioning Research*. 10 (2), pp131-136.

Bates, B. T., James, C. R. and Dufek, J. S. 2004. Single-subject analysis *IN*: Stergiou, N. *Innovative Analysis of Human Movement*. Leeds, U.K. Human Kinetics.

Bates, B. T. 1996. Single-subject methodology: an alternative approach. *Medicine and Science in Sport and Exercise*. 28 (5), pp631-638.

Bevan, H. R., Bunce, P. J., Owen, N. J., Bennett, M. A., Cook, C. J., Cunningham, D. J., Newton, R. U. and Kilduff, L. P. 2010. Optimal loading for the development of peak power output in professional rugby players. *Journal of Strength and Conditioning Research*. 24 (1), pp43-47.

Blazevich, A. J., Gill, N. D., Bronks, R. and Newton, R. U. 2003. Training-specific muscle architecture adaptation after 5-wk training in athletes. *Medicine and Science in Sport and Exercise*. 35 (12), pp2013-2022.

Bobbert, M. F. and Van Soest, A. J. 2001. Why do people jump the way they do? *Exercise and Sport Sciences Reviews*. 29 (3), pp95-102.

Bobbert, M. F. and Van Zandwijk, J. P. 1999. Dynamics of force and muscle stimulation in human vertical jumping. *Medicine and Science in Sport and Exercise*. 31 (20), pp303-310.

Bobbert, M. F., Gerritsen, K. G. M., Litjens, M. C. A. and Van Soest, A. J. 1996. Why is countermovement jump height greater than squat jump height? *Medicine and Science in Sport and Exercise*. 28 (11), pp1402-1412.

Bobbert, M. F. and Van Soest, A. J. 1994. Effects of muscle strengthening on vertical jump height: a simulation study. *Medicine and Science in Sport and Exercise*. 26 (8), pp1012-1020.

Bobbert, M. F. 1990. Drop jumping as a training method for jumping ability. *Sports Medicine*. 9 (1), pp7-22.

Bobbert, M. F. and van Ingen Schenau, G. J. 1988. Coordination in vertical jumping. *Journal of Biomechanics*. 21 (3), pp249-262.

Bobbert, M. F., Huijing, P. A. and van Ingen Schenau, G. J. (1987a). Drop jumping. I. The influence of jumping technique on the biomechanics of jumping. *Medicine and Science in Sport and Exercise*. 19 (4), pp332-338.

Bobbert, M. F., Huijing, P. A. and van Ingen Schenau, G. J. (1987b). Drop jumping.II. The influence of dropping height on the biomechanics of drop jumping. *Medicine and Science in Sport and Exercise*. 19 (4), pp339-346.

Bobbert, M. F., Mackay, M., Schinkelshoek, D., Huijing, P. A. and van Ingen Schenau, G. J. 1986a. Biomechanical analysis of drop and countermovement jumps. *European Journal of Applied Physiology*. 54 (6), pp566-573.

Bobbert, M. F., Huijing, P. A. and van Ingen Schenau, G. J. 1986b. An estimation of power output and work done by the human triceps surae muscle-tendon complex in jumping. *Journal of Biomechanics*. 19 (1), pp899-906.

Bojsen-Moller, F., Magnusson, S. P., Rasmussen, L. R., Kjaer, M. and Aagaard, P. 2005. Muscle performance during maximal isometric and dynamic contractions is influenced by the stiffness of the tendinous structures. *Journal of Applied Physiology*. 99, pp986-994.

Bosco, C., Komi, P. V. and Ito, A. Prestretch potentiation of human skeletal muscle during ballistic movement. 1981. *Acta Physiologica Scandinavica*. 111 (2), pp135-140.

Bosco, C. and Komi, P. V. 1979. Mechanical characteristics and fiber composition in human leg extensor muscles. *Journal of Applied Physiology*. 41, pp275-284.

Brown, M. E., Mayhew, J. L. and Boleach, L. W. 1986. Effect of plyometric training on vertical jump performance in high school basketball players. *The Journal of Sports Medicine and Physical Fitness*. 26 (1), pp1-4.

Cavagna, G. A., Dusman, B. and Margaria, R. 1968. Positive work done by a previously stretched muscle. *Journal of Applied Physiology*. 24 (1), pp21-32.

Cavagna, G. A., Saibene, F. P. and Margaria, R. 1965. Effect of negative work on the ammount of positive work performed by an isolated muscle. *Journal of Applied Physiology*. 20 (1), pp157-158.

Channell, B. T. and Barfield, J. P. 2008. Effect of Olympic and traditional resistance training on vertical jump improvement in high school boys. *Journal of Strength and Conditioning Research*. 22 (5), pp1522-1527.

Clark, J. E., Phillips, S. J. and Petersen, R. 1989. Developmental stability in jumping. *Developmental Psychology*. 25 (6), pp929-935.

Cormack, S. J., Newton, R. U., McGuigan, M. R. and Doyle, T. L. A. 2008. Reliability of measures obtained during single and repeated countermovement jumps. *International Journal of Sports Physiology and Performance*. 3 (2), pp131-144.

Cormie, P., McBride, J. M. and McCaulley, G. O. 2009. Power-time, force-time, and velocity-time curve analysis of the countermovement jump: impact of training. *Journal of Strength and Conditioning Research*. 23 (1), pp177-186.

Cormie, P., McBride, J. M. and McCaulley, G. O. 2008. Power-time, force-time, and velocity-time curve analysis during the jump squat: impact of load. *Journal of Applied Biomechanics*. 24 (2), pp112-120.

Cormie, P., McBride, J. M. and McCaulley, G. O. 2007a. Validation of power measurement techniques in dynamic lower body resistance exercises. *Journal of Applied Biomechanics*. 23 (2), pp103-118.

Cormie, P., McCaulley, G. O. and McBride, J. M. 2007b. Power versus strength-power jump squat training: influence on the load-power relationship. *Medicine and Science in Sport and Exercise*. 39 (6), pp996-1003.

Cormie, P., McCaulley, G. O., Triplett, N. T. and McBride, J. M. 2007c. Optimal loading for maximal power output during lower-body resistance exercises. *Medicine and Science in Sport and Exercise*. 39 (2), pp340-349.

Crewther, B., Cronin, J. and Keogh, J. 2005. Possible stimuli for strength and power adaptation. *Sports Medicine*. 35 (11), pp967-989.

De Villarreal, E. S. S., Kellis, E., Kraemer, W. J. and Izquierdo, M. 2009. Determining variables of plyometric training for improving jump height performance: a meta-analysis. *Journal of Strength and Conditioning Research*. 23 (2), pp495-506.

Dowling, J. J. and Vamos, L. 1993. Identification of kinetic and temporal factors related to vertical jump performance, *Journal of Applied Biomechanics*. 9, pp95-110.

Dufek, J. S., Bates, B. T., Stergiou, N. and James, C. R. 1995. Interactive effects between group and single-subject response patterns. *Human Movement Science*. 14 (3), pp301-323.

Dugan, E. L., Doyle, T. L. A., Humphries, B., Hasson, C. J. and Newton, R. U. 2004. Determining the optimal load for jump squats: a review of methods and calculations. *Journal of Strength and Conditioning Research*. 18 (3), pp668-674.

Earle, R. W. and Baechle, T. R. 2000. Resistance training and spotting techniques *IN*: Baechle, T.R. and Earle, R.W. (eds.). *Essentials of Strengh Training and Conditioning*. Second edition. Leeds, U.K. Human Kinetics.

Enoka, R. M. 1988. Load- and skill-related changes in segmental contributions to a weightlifting movement. *Medicine and Science in Sport and Exercise*. 20 (2), pp178-187.

Escamilla, R. F., Fleisig, G. S., Zheng, N., Lander, J. E., Barrentine, S. W., Andrews, J. R., Bergemann, B. W. and Moorman, C. T. 2001. Effects of technique variations on knee biomechanics during the squat and leg press. *Medicine and Science in Sport and Exercise*. 33 (9), pp1552-1566.

Feltner, M. E., Fraschetti, D. J. and Crisp, R. J. 1999. Upper extremity augmentation of lower extremity kinetics during countermovement vertical jumps. *Journal of Sports Sciences*. 17 (6), pp449-466.

Field, A. 2005. *Discovering Statistics Using SPSS*. Second edition. London: Sage Publications.

Finni, T., Komi, P. V. and Lepola, V. 2000. In vivo human triceps surae and quadriceps femoris muscle function in a squat jump and countermovement jump. *European Journal of Applied Physiology*. 83 (4-5), pp416-426.

Fowler, N. E. and Lees, A. 1998. A comparison of the kinetic and kinematic characteristics of plyometric drop-jump and pendulum exercises. *Journal of Applied Biomechanics*. 14, pp. 260-275.

Fry, A. C., Smith, J. C. and Schilling, B. 2003. Effect of knee position on hip and knee torques during the barbell squat. *Journal of Strength and Conditioning Research*. 17 (4), pp629-633.

Fukashiro, S. and Komi, P. V. 1987. Joint moment and mechanical power flow of the lower limb during vertical jump. *International Journal of Sports Medicine*. 8 (5), pp15-21.

Garhammer, J. 1993. A review of power output studies of olympic and powerlifting: methodology, performance prediction, and evaluation tests. *Journal of Strength and Conditioning Research*. 7 (2), pp76-89.

Gehri, D. J., Ricard, M. D., Douglas, M. K. and Kirkendall, D. T. 1998. A comparison of plyometric training techniques for improving vertical jump ability and energy production. *Journal of Strength and Conditioning Research*. 12 (2), pp85-89.

Hair, J. F., Anderson, R. E. and Tatham, R. L. 1987. *Multivariate Data Analysis*. Second edition. New York: Macmillan Publishing Company.

Harris, R.T. and Dudley, G. 2000. Neuromuscular anatomy and adaptations to conditioning *IN*: Baechle, T.R. and Earle, R.W. (eds.). *Essentials of Strengh Training and Conditioning*. Second edition. Leeds, U.K. Human Kinetics.

Harman, E. A., Rosenstein, M. T., Frykman, P. N. and Rosenstein, R. M. 1990. The effects of arms and countermovement on vetical jumping. *Medicine and Science in Sport and Exercise*. 22 (6), pp825-833.

Hoffman, J. R., Ratamess, N. A., Cooper, J. J., Kang, J., Chilakos, A. and Faigenbaum, A. D. 2005. Comparison of loaded and unloaded jump squat training on strength/power performance in college football players. *Journal of Strength and Conditioning Research*. 19 (4), pp810-815.

Hoffman, J. R., Cooper, J., Wendell, M. and Kang, J. 2004. Comparison of olympic vs. traditional power lifting training programs in football players. *Journal of Strength and Conditioning Research*. 18 (1), pp129-135.

Holcomb, W. R., Lander, J. E., Rutland, R. M. and Wilson, G. D. 1996a. A biomechanical analysis of the vertical jump and three modified plyometric depth jumps. *Journal of Strength and Conditioning Research*. 10 (2), pp83-88.

Holcomb, W. R., Lander, J. E., Rutland, R. M. and Wilson, G. D. 1996b. The effectivness of a modified plyometric program on power and the vertical jump. *Journal of Strength and Conditioning Research*. 10 (2), pp89-92.

Hori, N., Newton, R. U., Kawamori, N., McGuigan, M. R., Kraemer, W. J. and Nosaka, K. 2009. Reliability of performance measurements derived from ground reaction force data during countermovement jump and the influence of sampling frequency. *Journal of Strength and Conditioning Research*. 23 (3), pp874-882.

Hori, N., Newton, R. U., Kawamori, N., McGuigan, M. R., Andrews, W. A., Chapman, D. W. and Nosaka, K. 2008. Comparison of weighted jump squat training with and without eccentric breaking. *Journal of Strength and Conditioning Research*. 22 (1), pp54-65.

Hori, N., Newton, R. U., Nosaka, K. and Stone, M. 2005. Weightlifting exercises enhance athletic performance that requires high-load speed strength. *Strength and Conditioning Journal*. 27 (4), pp50-55.

Howard, J. G. 1997. *Effect of an eight-week power clean or squat training program on anaerobic power, peak force, max velocity, and vertical jump performance in beginning weight lifters*. Masters Thesis. Utah State University.

Hubley, C. L. and Wells, R. P. 1983. A work-energy approach to determine individual joint contributions to vertical jump performance. *European Journal of Applied Physiology*. 50 (2), pp247-254.

Hudson, J. L. 1986. Coordination of segments in the vertical jump. *Medicine and Science in Sport and Exercise*. 18 (2), pp242-251.

Hunter, J. P. and Marshall, R. N. 2002. Effects of power and flexibility training on vertical jump technique. *Medicine and Science in Sport and Exercise*. 34 (3), pp 478-486.

James, C. R. 2004. Considerations of movement variability in biomechanics research *IN*: Stergiou, N. (ed.). *Innovative Analyses of Human Movement*. Leeds, U.K. Human Kinetics.

Jaric, S., Ristanovic, D. and Corcos, D. M. 1989. The relationship between muscle kinetic parameters and kinematic variables in a complex movement. *European Journal of Applied Physiology*. 59 (5), pp370-376.

Jensen, J. L., Phillips, S. J. and Clark, J. E. 1994. For young jumpers, differences are in movement's control, not its coordination. *Research Quarterly for Exercise and Sport*. 65 (3), pp258-268.

Jones, S. L. and Caldwell, G. E. 2003. Mono- and biarticular muscle activity during jumping in different directions. *Journal of Applied Biomechanics*. 19 (3), pp205-222.

Kawamori, N., Rossi, S. J., Justice, B. D., Haff, E. E., Pistilli, E. E., O'Bryant, H. S., Stone, M. and Haff, G. G. 2006. Peak force and rate of force development during isometric and dynamic mid-thigh clean pulls performed at various intensities. *Journal of Strength and Conditioning Research*. 20 (3), pp483-491.

Kawamori, N. and Haff, G. 2004. The optimal training load for the development of muscular power. *Journal of Strength and Conditioning Research*. 18 (3), pp675-684.

Kinsella, S. and Moran, K. A. 2008. Gait pattern categorization of stroke participants with equinus deformity of the foot. *Gait and Posture*. 27 (1), pp144-151.

Knudson, D., Bennet, K., Corn, R., Leick, D. and Smith, C. 2001. Acute effects of stretching are not evident in the kinematics of the vertical jump. *Journal of Strength and Conditioning Research*. 15 (1), pp98-101.

Kollias, I., Panoutsakopoulos, V. and Papaiakovou, G. 2004. Comparing jumping ability among athletes of various sports: vertical drop jumping from 60 centimeters. *Journal of Strength and Conditioning Research.* 18 (3), pp546-550.

Kraemer, W. J. and Newton, R. U. 1994. Training for improved vertical jump. *Sports Science Exchange.* 7 (6), pp1-5.

Latash, M. L., Scholz, J. P. and Schoner, G. 2007. Toward a new theory of motor synergies. *Motor Control.* 11 (3), pp276-308.

Latash, M. L., Scholz, J. P. and Schoner, G. 2002. Motor control strategies revealed in the structure of motor control. *Exercise and Sport Sciences Reviews.* 30 (1), pp26-31.

Lees, A. 2000. Technique analysis in sports: a critical review. *Journal of Sports Sciences.* 20 (10), pp813-828.

Lees, A. and Fahmi, E. 1994. Optimal drop heights for plyometric training. *Ergonomics.* 37 (1), pp141-148.

Leubbers, P. E., Potteiger, J. A., Hulver, M. W., Thyfault, J. P., Carper, M. J. and Lockwood, R. H. 2003. Effects of plyometric training and recovery on vertical jump performance and anaerobic power. *Journal of Strength and Conditioning Research.* 17 (4), pp704-709.

Lyttle, A. D., Wilson, G. J. and Ostrowski, K. J. 1996. Enhancing performance: maximal power versus combined weights and plyometrics training. *Journal of Strength and Conditioning Research.* 10 (3), pp173-179.

Markovic, G., Jukic, I., Milanovic, D. and Metikos, D. 2007. Effects of sprint and plyometric training on muscle function and athletic performance. *Journal of Strength and Conditioning Research.* 21 (2), pp543-549.

Matavulj, D., Kukolj, M., Ugarkovic, D., Tihanyi, J. and Jaric, S. 2001. Effects of plyometric training on jumping performance in junior basketball players. *Journal of Sports Medicine and Physical Fitness.* 41 (2), pp159-164.

McBride, J. M., Triplett-McBride, T., Davie, A. and Newton, R. U. 2002. The effect of heavy- Vs. light-load jump squats on the development of strength, power and speed. *Journal of Strength and Conditioning Research.* 16 (1), pp75-82.

Moir, G. L., Garcia, A. and Dwyer, G. B. 2009. Intersession reliability of kinematic and kinetic variables during vertical jumps in men and women. *International Journal of Sports Physiology and Performance.* 4 (3), pp317-330.

Moran, K. A. and Wallace, E. S. 2007. Eccentric loading and range of knee joint motion effects on perfomance enhancement in vertical jumping. Human Movement Science 26 (6), pp824-840.

Moran, K. A. 1998. *A biomechanical evaluation of the effect of the stretch shortening cycle in unconstrained and experimentally constrained vertical jumps*. PhD Thesis. University of Ulster.

Morrisey, M. C., Harman, E. A., Frykman, P. N. and Han, K. H. 1998. Early phase differential effects of slow and fast barbell squat training, *The American Journal of Sports Medicine*. 26 (2), pp221-230.

Muller, H. and Sternad, D. 2009. Motor learning: changes in the structure of variability in a redundant task. *Advances in Experimental Medicine and Biology*. 629, pp439-456.

Newton, R. U. and Dugan, E. 2002. Application of strength diagnosis. *Strength and Conditioning Journal*. 24 (5), pp50-59.

Newton, R. U., Kraemer, W. J. and Hakkinen, K. 1999. Effects of ballistic training on preseason preparation of elite volleyball players. *Medicine and Science in Sport and Exercise*. 31(2), pp323-330.

Park, R. S., Chibnall, J. T. and Morrow, A. 2005. Relationship of rotation timing to pattern of clerkship performance in psychiatry. *Academic Psychiatry*. 29 (3), pp267-273.

Potach, D. H. and Chu, D. A. 2000. Plyometric training *IN*: Baechle, T.R. and Earle, R.W (eds.). *Essentials of Strengh Training and Conditioning*. Second edition. Leeds, U.K. Human Kinetics.

Potteiger, J. A., Lockwood, R. H., Haub, M. D., Dolezal, B. A., Almuzaini, K. S., Schroeder, J. M. and Zebas, C. J. 1999. Muscle power and fiber characteristics following 8 weeks of plyometric training. *Journal of Strength and Conditioning Research.* 13(3), pp275-279.

Rahmani, A., Viale, F., Dalleau, G. and Lacour, JR. 2001. Force/velocity and power/velocity relationships in squat exercise. *European Journal of Applied Physiology*. 84 (3), pp227-232.

Ravn, S., Voigt, M., Simonsen, E. B., Alkjaer, T., Bojsen-Moller, F. and Klausen, K. 1999. Choice of jumping strategy in two standard jumps, squat and countermovement jump-effect of training background or inherited preference? *Scandinavian Journal of Medicine and Science in Sports*. 9 (4), pp201-208.

Read, M. M. and Cisar, C. 2001. The influence of varied rest interval lengths on depth jump performance. *Journal of Strength and Conditioning Research.* 15 (3), pp279-283.

Rodacki, A. L. F., Fowler, N. E. and Bennett, S. J. 2002. Vertical jump coordination: fatigue effects. *Medicine and Science in Sport and Exercise*. 34 (1), pp105-116.

Rodacki, A. L. F., Fowler, N. E. and Bennett, S. J. 2001. Multi-segment coordination: fatigue effects. *Medicine and Science in Sport and Exercise*. 33 (7), pp1157-1167.

Rodano, R. and Squadrone, R. 2002. Stability of selected lower limb joint kinetic parameters during vertical jump. *Journal of Applied Biomechanics*. 18 (1), pp83-89.

Schmidtbleicher, D. 1992. Training for power events *IN*: Komi, P.V. (ed.). *Strength and Power in Sport*. London: Blackwell scientific publications.

Shepard, J. M., Chapman, D. W., Gough, C., McGuigan, M. R. and Newton, R. U. 2009. Twelve-month training-induced changes in elite international volleyball players. *Journal of Strength and Conditioning* Research. 23 (7), pp2096-2101.

Souza, A. L., Shimada, S. D. and Koontz, A. 2002. Ground reaction forces during the power clean. *Journal of Strength and Conditioning Research*. 16 (3), pp423-427.

Stephens, T. M., Lawson, B. R., DeVoe, D. E. and Reiser, R. F. 2007. Gender and bilateral differences in single-leg countermovement jump performance with comparison to a double-leg jump. *Journal of Applied Biomechanics*. 23 (3), pp190-202.

Stergiou, N. and Scott, M. M. 2005. Baseline measures are altered in biomechanical studies. *Journal of Biomechanics*. 38(1), pp175-178.

Stergiou, N., Buzzi, U. H., Kurz, M. J. and Heidel, J. 2004. Nonlinear tools in human movement *IN*: Stergiou, N (ed.). *Innovative Analysis of Human Movement*. Leeds, U.K. Human Kinetics.

Stone, M. H., O'Bryant, H. S., McCoy, L., Coglianese, R., Lehmkuhl, M. and Schilling, B. 2003. Power and maximum strength relationships during performance of dynamic and static weighted jumps. *Journal of Strength and Conditioning Research*. 17 (1), pp140-147.

Takarada, Y., Hirano, Y., Ishige, Y. and Ishii, N. 2007. Stretch-induced enhancement of mechanical power output in human multijoint exercise with countermovement. *Journal of applied physiology*. 83 (5), pp1749-1755.

Thomas, G. A., Kraemer, W. J., Spiering, B. A., Volek, J. S., Anderson, J. M. and Maresh, C. M. 2007. Maximal power at different percentages of one repetition maximum: influence of resistance and gender. *Journal of Strength and Conditioning Research*. 21 (2), pp336-342.

Tomioka, M., Owings, T. M. and Grabiner, M. D. 2001. Lower extremity strength and coordination are independent contributors to maximum vertical jump height. *Journal of Applied Biomechanics*. 17 (3), pp181-187.

Toumi, H., Best, T. M., Matin, A. and Poumarat, G. 2004. Muscle plasticity after weight and combined (weight + jump) training. *Medicine and Science in Sport and Exercise*. 36 (9), pp1580-1588.

Tricoli, V., Lamas, L., Carnevale, R. and Ugrinowitsch, C. 2005. Short-term effects on lower-body functional power development: weightlifting vs. vertical jump training programs. *Journal of Strength and Conditioning Research*. 19 (2), pp433-437.

Ugrinowitsch, C., Tricoli, V., Rodacki, A. L. F., Batista, M. and Ricard, M. D. 2007. Influence of training background on jumping height. *Journal of Strength and Conditioning Research*. 21 (3), pp848-852.

Umberger, B. R. 1998. Mechanics of the vertical jump and two-joint muscles: implications for training. *Strength and Conditioning Journal*. 20 (5), pp70-74.

Van Ingen Schenau, G. J. 1989. From rotation to translation: constraints on multi-joint movements and the unique action of bi-articular muscles. *Human Movement Science*. 8 (4), pp301-337.

Van Soest, A. J., Roebroeck, M. E., Bobbert, M. F., Huijing, P. A. and Van Ingen Schenau, G. J. 1985. A comparison of one-legged and two-legged countermovement jumps. *Medicine and Science in Sport and Exercise*. 17 (6), pp 635-639.

Vanezis, A. and Lees, A. 2005. A biomechanical analysis of good and poor performers of the vertical jump. *Ergonomics*. 48, pp1594-1603.

Vanrenterghem, J., Lees, A. and De Clerq, D. 2008. Effect of forward trunk inclination on joint power output in vertical jumping. *Journal of Strength and Conditioning Research*. 22(3), pp708-714.

Vanrenterghem, J., De Clerq, D. and van Cleven, P. 2001. Necessary precautions in measuring correct vertical jumping height by means of force plate measurements. *Ergonomics*. 44, pp814-818.

Viitasalo, J. T., Salo, A. and Lahtinen, J. 1998. Neuromuscular functioning of athletes and non-athletes in the drop jump. *European Journal of Applied Physiology*. 78 (5) pp432-440.

Voigt, M., Simonsen, E. B., Dyhre-Poulson, P. and Klausen, K. 1995. Mechanical and muscular factors influencing the performance in maximal vertical jumping after different prestretch loads. *Journal of Biomechanics*. 28 (3), pp293-307.

Walsh, M., Arampatzis, A., Schade, F. and Bruggemann, GP. 2004. The effect of drop jump starting height and contact time on power, work performed, and moment of force. *Journal of Strength and Conditioning Research*. 18 (3), pp561-566.

Weiss, L. W., Fry, A. C., Wood, L. E., Relyea, G. E. and Melton, C. 2000. Comparative effects of deep versus shallow squat and leg-press training on vertical jumping ability and related factors. *Journal of Strength and Conditioning Research*. 14 (3), pp241-247.

Weiss, L. W., Coney, H. D. and Clark, F. C. 1999. Differential functional adaptations to short-term low-, moderate-, and high-repetition weight training. *Journal of Strength and Conditioning Research*. 13 (3), pp236-241.

Wilson, G. J., Murphy, A. J. and Giorgi, A. 1996. Weight and plyometric training: effects on eccentric and concentric force production. *Canadian Journal of Applied Physiology*. 21 (4), pp301-315.

Wilson, G. J., Lyttle, A. D., Ostrowski, K. J. and Murphy, A. J. 1995. Assessing dynamic performance: a comparison of rate of force development tests. *Journal of Strength and Conditioning Research*. 9 (3), pp176-181.

Wilson, G. J., Newton, R. U., Murphy, A. J. and Humphries, B. J. 1993. The optimal training load for the development of dynamic athletic performance. *Medicine and Science in Sport and Exercise*. 25 (11), pp1279-1286.

Winchester, J. B., Erickson, T. M., Blaak, J. B. and McBride, J. M. 2005. Changes in bar-path kinematics and kinetics after power-clean training. *Journal of Strength and Conditioning Research*. 19 (1), pp177-183.

Winter, D. A. 1990. *Biomechanics and Motor Control of Human Movement*. New York: Wiley-Interscience.

Wretenberg, P., Feng, Y. and Arborelius, U. P. 1996. High- and low- bar squatting techniques during weight-training. *Medicine and Science in Sport and Exercise*. 28 (2), pp218-224.

Young, W. B., Wilson, G. J. and Byrne, C. 1999. A comparison of drop jump training methods: effects on leg extensor strength qualities and jumping performance. *International Journal of Sports Medicine*. 20 (5), pp295-303.

Young, W., Pryor, J. F. and Wilson, G. 1995. Effect of instructions on characteristics of countermovement and drop jump performance. *Journal of Strength and Conditioning Research*. 9 (4), pp232-236.

Young, W. B. and Bilby, G. E. 1993. The effect of volunatary effort to influence speed of contraction on strength, muscular power, and hypertrophy development. *Journal of Strength and Conditioning Research*. 7 (3), pp172-178.

Zajac, F. 1993. Muscle coordination of movement: a perspective. *Journal of Biomechanics*. 26 (1), pp109-124.

Zatsiorsky, V. M. and Kraemer, W. J. 2006. *Science and Practise of Strength Training*. Leeds: Human Kinetics.

Appendix A: The individual level results for subjects A-O (study 2)

Subject A: Significant 5cm (14%) post-training increase in CMJ jump height.

Table A1 The acute pre-training stress experienced by, and post-training magnitude changes in, subject A's CMJ PRFs

	A	B	C	D	E
CMJ PRFs	r	Acute pre-training stress (% diff CMJ vs DJ)	Expected training effect	Post-training change (% change)	Accuracy of expected training effect
Time between peak power at the knee and ankle (ms)	-0.69	Inappropriate (100%) *	Decline	Decline (+47%) **	Accurate
Eccentric phase duration (ms)	-0.65	Appropriate (-64%) *	Enhancement	Enhancement (-19%) **	Accurate
Hip concentric peak power (W. Kg^{-1})	0.61	No stress (-8%)	No change	Enhancement (+60%) **	Inaccurate
Ankle moment at joint reversal (Nm.kg^{-1})	0.57	Appropriate (117%) *	Enhancement	Enhancement (+49%) **	Accurate
Time between peak moment at the knee and ankle (ms)	-0.57	Appropriate (-77%) *	Enhancement	Enhancement (-16%) **	Accurate
Time between joint reversal at the knee and ankle (ms)	-0.55	Appropriate (-90%) *	Enhancement	Enhancement (-32%) **	Accurate

* Significant difference CMJ Pre versus DJ pre ($p<0.05$)

** Significant difference CMJ Pre versus CMJ post ($p<0.05$)

RED: PRF negatively correlated with jump height means a smaller magnitude was associated with larger jump heights

Subject B: Significant 5cm (11%) post-training increase in CMJ jump height

Table A2 The acute pre-training stress experienced by, and post-training magnitude changes in, subject B's CMJ PRFs

	A	B	C	D	E
CMJ PRFs	r	Acute pre-training stress (% diff CMJ vs DJ)	Expected training effect	Post-training change (% change)	Accuracy of expected training effect
Knee concentric peak moment (Nm.kg^{-1})	0.70	Appropriate (144%) *	Enhancement	Enhancement (+5%) **	Accurate
Concentric phase duration (ms)	-0.67	Appropriate (-57%) *	Enhancement	Enhancement (-14%) **	Accurate
Knee moment at joint reversal (Nm.kg^{-1})	0.66	Appropriate (414%) *	Enhancement	Enhancement (+36%) **	Accurate
Ankle angle at joint reversal (deg) †	-0.64	No stress (-3%)	No change	Decline (+13%) **	Inaccurate
Hip eccentric stiffness (N.kg^{-1}.m^{-1})	0.62	Appropriate (516%) *	Enhancement	Enhancement (+25%) **	Accurate
Whole body concentric rate of power development (W.kg^{-1}.s^{-1})	0.62	Appropriate (382%) *	Enhancement	Enhancement (+33%) **	Accurate

* Significant difference CMJ Pre versus DJ pre ($p<0.05$)

** Significant difference CMJ Pre versus CMJ post ($p<0.05$)

Red: PRF negatively correlated with jump height means a smaller magnitude was associated with larger jump heights

† A more flexed ankle at joint reversal (indicating a greater ROM) was associated with larger jump heights

Table A2 Continued overleaf

Table A2 (Continued) The acute pre-training stress experienced by, and post-training magnitude changes in, subject B's CMJ PRFs

	A	B	C	D	E
CMJ PRFs	r	Acute pre-training stress (% diff CMJ vs DJ)	Expected training effect	Post-training change (% change)	Accuracy of expected training effect
Ratio of early concentric impulse to late eccentric impulse	-0.59	Appropriate (-11%) *	Enhancement	Enhancement (-9%) **	Accurate
Vertical ground reaction force at the low point of the bodies COM ($N.kg^{-1}$)	0.59	Appropriate (113%) *	Enhancement	Enhancement (+24%) **	Accurate
Ankle concentric rate of power development ($W.kg^{-1}.s^{-1}$)	0.59	Appropriate (117%) *	Enhancement	No change (-13%)	Inaccurate
Whole body eccentric stiffness ($N.kg^{-1}.m^{-1}$)	0.53	Appropriate (833%) *	Enhancement	Enhancement (+48%) **	Accurate

* Significant difference CMJ Pre versus DJ pre ($p<0.05$)

** Significant difference CMJ Pre versus CMJ post ($p<0.05$)

Red: PRF negatively correlated with jump height means a smaller magnitude was associated with larger jump height

Subject C: Significant 5cm (10%) post-training increase in CMJ jump height

Table A3 The acute pre-training stress experienced by, and post-training magnitude changes in, subject C's CMJ PRFs

	A	B	C	D	E
CMJ PRFs	r	Acute pre-training stress (% diff CMJ vs DJ)	Expected training effect	Post-training change (% change)	Accuracy of expected training effect
Hip eccentric work done ($J.kg^{-1}$)	0.82	No stress (-63%) *	No change	Enhancement (+171%) **	Inaccurate
Hip concentric peak moment ($Nm.kg^{-1}$)	0.78	No stress (-6%)	No change	Enhancement (+87%) **	Inaccurate
Hip moment at joint reversal ($Nm.kg^{-1}$)	0.71	No stress (-3%)	No change	Enhancement (+90%) **	Inaccurate
Hip concentric work done ($J.kg^{-1}$)	0.71	No stress (-68%) *	No change	Enhancement (+129%) **	Inaccurate
Hip concentric rate of power development ($W.kg^{-1}.s^{-1}$)	0.69	Appropriate (134%) *	Enhancement	Enhancement (+91%) **	Accurate

* Significant difference CMJ Pre versus DJ pre ($p<0.05$)

** Significant difference CMJ Pre versus CMJ post ($p<0.05$)

Table A3 continued overleaf

Table A3 (Continued) The acute pre-training stress experienced by, and post-training magnitude changes in, subject C's CMJ PRFs

	A	B	C	D	E
CMJ PRFs	r	Acute pre-training stress (% diff CMJ vs DJ)	Expected training effect	Post-training change (% change)	Accuracy of expected training effect
Amplitude of the centre of mass (cm)	0.68	Inappropriate (-55%) *	Decline	Decline (-13%) **	Accurate
Whole body eccentric peak vertical velocity ($m.s^{-1}$)	0.68	Appropriate (156%) *	Enhancement	No change (+6%)	Inaccurate
Whole body concentric work done ($J.kg^{-1}$)	0.68	No stress (-26%) *	No change	Enhancement (+18%) **	Inaccurate
Hip angle at joint reversal (deg) †	-0.67	Inappropriate (131%) *	Decline	Decline (+9%) **	Accurate
Whole body eccentric impulse ($N.kg^{-1}.s$)	0.67	Appropriate (121%) *	Enhancement	No change (+4%)	Inaccurate

* Significant difference CMJ Pre versus DJ pre ($p<0.05$)
** Significant difference CMJ Pre versus CMJ post ($p<0.05$)
Red: PRF negatively correlated with jump height means a smaller magnitude was associated with larger jump heights
† A more flexed hip at joint reversal (indicating a greater ROM) was associated with larger jump heights

Subject D: Significant 3cm (6%) post-training increase in CMJ jump height

Table A4 The acute pre-training stress experienced by, and post-training magnitude changes in, subject D's CMJ PRFs

	A	**B**	**C**	**D**	**E**
CMJ PRFs	r	Acute pre-training stress (% diff CMJ vs DJ)	Expected training effect	Post-training change (% change)	Accuracy of expected training effect
Whole body concentric peak power ($W.kg^{-1}$)	0.78	Appropriate (49%) *	Enhancement	Enhancement (+9%) **	Accurate
Hip concentric peak power ($W. Kg^{-1}$)	0.63	No stress (-1%)	No change	Enhancement (+ 23%) **	Inaccurate
Knee concentric peak moment ($Nm.kg^{-1}$)	0.52	Appropriate (142%) *	Enhancement	No change (+ 2%)	Inaccurate

* Significant difference CMJ Pre versus DJ pre ($p<0.05$)

** Significant difference CMJ Pre versus CMJ post ($p<0.05$)

Subject E: Significant 2cm (5%) post-training increase in CMJ jump height

Table A5 The acute pre-training stress experienced by, and post-training magnitude changes in, subject E's CMJ PRFs

	A	B	C	D	E
CMJ PRFs	r	Acute pre-training stress (% diff CMJ vs DJ)	Expected training effect	Post-training change (% change)	Accuracy of expected training effect
Hip concentric peak power ($W. Kg^{-1}$)	0.75	No stress (-12%)	No change	Enhancement (+26%) **	Inaccurate
Ratio of late ankle eccentric work done to early ankle concentric work done	0.63	No stress (-28%)	No change	No change (-10%)	Accurate
Hip concentric peak moment ($Nm.kg^{-1}$)	0.58	No stress (0%)	No change	Enhancement (+33%) **	Inaccurate
Hip concentric work done ($J.kg^{-1}$)	0.56	No stress (-61%) *	No change	Enhancement (+18%) **	Inaccurate
Hip concentric rate of power development ($W.kg^{-1}.s^{-1}$)	0.51	No stress (+12%)	No change	Enhancement (+55%) **	Inaccurate

* Significant difference CMJ Pre versus DJ pre ($p<0.05$)
** Significant difference CMJ Pre versus CMJ post ($p<0.05$)

Subject F: No significant post-training change in CMJ jump height

Table A6 The acute pre-training stress experienced by, and post-training magnitude changes in, subject F's CMJ PRFs

	A	B	C	D	E
CMJ PRFs	r	Acute pre-training stress (% diff CMJ vs DJ)	Expected training effect	Post-training change (% change)	Accuracy of expected training effect
Knee concentric peak power (W. Kg^{-1})	0.78	Appropriate (76%) *	Enhancement	No change (-1%)	Inaccurate
Time between peak moment at the hip and knee (ms)	0.73	Inappropriate (-155%) *	Decline	No change (+10%)	Inaccurate
Knee concentric work done (J.kg^{-1})	0.71	Appropriate (35%) *	Enhancement	No change (-6%)	Inaccurate
Hip concentric peak moment (Nm.kg^{-1})	0.68	No stress (-4%)	No change	Enhancement ** (+27%)	Inaccurate
Time between peak moment at the knee and ankle (ms)	-0.68	No stress (-12%)	No change	Enhancement ** (-79%)	Inaccurate

* Significant difference CMJ Pre versus DJ pre ($p<0.05$)
** Significant difference CMJ Pre versus CMJ post ($p<0.05$)
Red: PRF negatively correlated with jump height means a smaller magnitude was associated with larger jump heights

Table A6 continued overleaf

Table A6 (Continued) The acute pre-training stress experienced by, and post-training magnitude changes in, subject F's CMJ PRFs

	A	B	C	D	E
CMJ PRFs	r	Acute pre-training stress (% diff CMJ vs DJ)	Expected training effect	Post-training change (% change)	Accuracy of expected training effect
Ankle rate of power development at the start of the concentric phase ($W.kg^{-1}.s^{-1}$)	0.60	Appropriate (503%) *	Enhancement	No change (+1%)	Inaccurate
Knee concentric rate of power development ($W.kg^{-1}.s^{-1}$)	0.58	Appropriate (331%) *	Enhancement	No change (-2%)	Inaccurate
Hip concentric rate of moment development ($N.m.s^{-1}$)	0.58	Appropriate (272%) *	Enhancement	No change (+5%)	Inaccurate
Ankle moment at joint reversal ($Nm.kg^{-1}$)	0.51	Appropriate (78%) *	Enhancement	No change (+2%)	Inaccurate

* Significant difference CMJ Pre versus DJ pre ($p<0.05$)
** Significant difference CMJ Pre versus CMJ post ($p<0.05$)

Subject G: No significant post-training change in CMJ jump height

Table A7 The acute pre-training stress experienced by, and post-training magnitude changes in, subject G's CMJ PRFs

	A	B	C	D	E
CMJ PRFs	r	Acute pre-training stress (% diff CMJ vs DJ)	Expected training effect	Post-training change (% change)	Accuracy of expected training effect
Ratio of late hip eccentric work done to early hip concentric work done	-0.86	Appropriate (-29%) *	Enhancement	No change (+8%)	Inaccurate
Hip eccentric work done ($J.kg^{-1}$)	0.83	No stress (10%)	No change	Enhancement ** (+46%)	Inaccurate
Whole body eccentric work done ($J.kg^{-1}$)	0.73	Appropriate (75%) *	Enhancement	Decline ** (-6%)	Inaccurate
Hip concentric peak power ($W. Kg^{-1}$)	0.72	Appropriate (21%) *	Enhancement	Enhancement ** (+20%)	Accurate
Hip angle at joint reversal (deg) †	-0.71	Inappropriate (49%) *	Decline	No change (+1%)	Inaccurate

* Significant difference CMJ Pre versus DJ pre ($p<0.05$)
** Significant difference CMJ Pre versus CMJ post ($p<0.05$)
Red: PRF negatively correlated with jump height means a smaller magnitude was associated with larger jump heights
† A more flexed hip at joint reversal (indicating a greater ROM) is associated with larger jump heights

Table A7 continued overleaf

Table A7 (Continued) The acute pre-training stress experienced by, and post-training magnitude changes in, subject G's CMJ PRFs

	A	B	C	D	E
CMJ PRFs	r	Acute pre-training stress (% diff CMJ vs DJ)	Expected training effect	Post-training change (% change)	Accuracy of expected training effect
Ratio of late ankle eccentric work done to early ankle concentric work done	-0.70	No stress (5%)	No change	No change (+10%)	Accurate
Hip concentric work done (J.kg^{-1})	0.70	No stress (-25%) *	No change	Enhancement ** (+26%)	Inaccurate
Hip concentric peak moment (Nm.kg^{-1})	0.67	Appropriate (55%) *	Enhancement	Enhancement ** (+15%)	Accurate
Whole body concentric work done (J.kg^{-1})	0.65	No stress (-18%) *	No change	No change (-1%)	Accurate

* Significant difference CMJ Pre versus DJ pre ($p<0.05$)
** Significant difference CMJ Pre versus CMJ post ($p<0.05$)
Red: PRF negatively correlated with jump height means a smaller magnitude was associated with larger jump heights

Subject H: No significant post-training change in CMJ jump height

Table A8 The acute pre-training stress experienced by, and post-training magnitude changes in, subject H's CMJ PRFs

	A	**B**	**C**	**D**	**E**
CMJ PRFs	r	Acute pre-training stress (% diff CMJ vs DJ)	Expected training effect	Post-training change (% change)	Accuracy of expected training effect
Ratio of late ankle eccentric work done to early ankle concentric work done	-0.61	Appropriate (-82%) *	Enhancement	No change (-9%)	Inaccurate
Ratio of late WB eccentric work done to early WB concentric work done	0.61	No stress (-10%)	No change	Decline ** (-16%)	Inaccurate
Ankle eccentric stiffness (N.kg^{-1}.m^{-1})	0.58	Appropriate (95%) *	Enhancement	No change (+8%)	Inaccurate
Time between peak moment at the hip and knee (ms)	-0.56	Appropriate (-100%) *	Enhancement	Decline ** (+17%)	Inaccurate
Time between peak power and takeoff (ms)	-0.55	No stress (-6%)	No change	No change (-2%)	Accurate

*   Significant difference CMJ Pre versus DJ pre (p<0.05)
** Significant difference CMJ Pre versus CMJ post (p<0.05)
Red: PRF negatively correlated with jump height means a smaller magnitude was associated with larger jump heights

Subject I: No significant post-training change in CMJ jump height

Table A9 The acute pre-training stress experienced by, and post-training magnitude changes in, subject I's CMJ PRFs

	A	B	C	D	E
CMJ PRFs	r	Acute pre-training stress (% diff CMJ vs DJ)	Expected training effect	Post-training change (% change)	Accuracy of expected training effect
Hip concentric peak power (W. Kg^{-1})	0.73	No stress (-10%)	No change	Decline ** (-14%)	Inaccurate
Hip concentric peak moment ($Nm.kg^{-1}$)	0.69	Appropriate (40%) *	Enhancement	Decline ** (-7%)	Inaccurate
Hip concentric work done ($J.kg^{-1}$)	0.67	No stress (-46%) *	No change	Decline ** (-16%)	Inaccurate
Ankle angle at joint reversal (deg) †	0.59	No stress (-3%)	No change	No change (-2%)	Accurate

* Significant difference CMJ Pre versus DJ pre ($p<0.05$)

** Significant difference CMJ Pre versus CMJ post ($p<0.05$)

† A more extended ankle at joint reversal (indicating a smaller ROM) is associated with larger jump heights

Table A9 continued overleaf

Table A9 (Continued) The acute pre-training stress experienced by, and post-training magnitude changes in, subject I's CMJ PRFs

	A	B	C	D	E
CMJ PRFs	r	Acute pre-training stress (% diff CMJ vs DJ)	Expected training effect	Post-training change (% change)	Accuracy of expected training effect
Hip angle at joint reversal (deg) †	-0.55	Inappropriate (64%) *	Decline	Decline ** (+21%)	Accurate
Time between peak power and takeoff (ms)	-0.54	Inappropriate (13%) *	Decline	No change (+2%)	Inaccurate
Hip concentric rate of power development ($W.kg^{-1}.s^{-1}$)	0.53	Appropriate (125%) *	Enhancement	No change (-6%)	Inaccurate
Knee eccentric stiffness ($N.kg^{-1}.m^{-1}$)	-0.52	Inappropriate (343%) *	Decline	Decline ** (+18%)	Accurate

* Significant difference CMJ Pre versus DJ pre ($p<0.05$)

** Significant difference CMJ Pre versus CMJ post ($p<0.05$)

Red: PRF negatively correlated with jump height means a smaller magnitude was associated with larger jump heights

† A more flexed hip at joint reversal (indicating a greater ROM) is associated with larger jump heights

Subject J: No significant post-training change in CMJ jump height

Table A10 The acute pre-training stress experienced by, and post-training magnitude changes in, subject J's CMJ PRFs

	A	**B**	**C**	**D**	**E**
CMJ PRFs	r	Acute pre-training stress (% diff CMJ vs DJ)	Expected training effect	Post-training change (% change)	Accuracy of expected training effect
Time between peak power at the knee and ankle (ms)	-0.72	No stress (-7%)	No change	Enhancement (-18%) **	Inaccurate
Time between peak moment at the hip and knee (ms)	0.66	Inappropriate (-79%) *	Decline	No change (-4%)	Inaccurate
Hip concentric peak power (W. Kg^{-1})	0.64	No stress (-8%)	No change	No change (0%)	Accurate
Whole body concentric work done (J.kg^{-1})	0.62	No stress (-21%) *	No change	Decline ** (-9%)	Inaccurate
Whole body eccentric work done (J.kg^{-1})	0.61	Appropriate (57%) *	Enhancement	Decline ** (-11%)	Inaccurate
Ankle eccentric work done (J.kg^{-1})	0.60	Appropriate (455%) *	Enhancement	Enhancement ** (+20%)	Accurate

* Significant difference CMJ Pre versus DJ pre ($p<0.05$)
** Significant difference CMJ Pre versus CMJ post ($p<0.05$)
Red: PRF negatively correlated with jump height means a smaller magnitude was associated with larger jump heights

Table A10 continued overleaf

Table A10 (Continued) The acute pre-training stress experienced by, and post-training magnitude changes in, subject J's CMJ PRFs

	A	B	C	D	E
CMJ PRFs	r	Acute pre-training stress (% diff CMJ vs DJ)	Expected training effect	Post-training change (% change)	Accuracy of expected training effect
Knee angle at joint reversal (deg)	-0.57	Inappropriate (8%) *	Decline	Decline ** (+7%)	Accurate
Hip eccentric work done (J.kg^{-1})	0.57	No stress (-28%) *	No change	Decline ** (-8%)	Inaccurate
Amplitude of the centre of mass (cm)	0.57	Inappropriate (-32%) *	Decline	Decline ** (-14%)	Accurate
Hip angle at joint reversal (deg)	-0.56	Inappropriate (122%) *	Decline	Decline ** (+50%)	Accurate
Hip concentric work done (J.kg^{-1})	0.56	No stress (-52%) *	No change	Decline ** (-12%)	Inaccurate
Whole body eccentric impulse (N.kg^{-1}.s)	0.55	Appropriate (189%) *	Enhancement	Enhancement ** (+14%)	Accurate

* Significant difference CMJ Pre versus DJ pre ($p<0.05$)

** Significant difference CMJ Pre versus CMJ post ($p<0.05$)

Red: PRF negatively correlated with jump height means a smaller magnitude was associated with larger jump heights

Subject K: Significant 6cm (11%) post-training decrease in CMJ jump height.

Table A11 The acute pre-training stress experienced by, and post-training magnitude changes in, subject K's CMJ PRFs

	A	B	C	D	E
CMJ PRFs	r	Acute pre-training stress (% diff CMJ vs DJ)	Expected training effect	Post-training change (% change)	Accuracy of expected training effect
Ankle angle at joint reversal (deg) †	-0.78	Inappropriate (8%) *	Decline	No change (+2%)	Inaccurate
Hip concentric work done ($J.kg^{-1}$)	0.78	No stress (-90%) *	No change	Decline ** (-12%)	Inaccurate
Whole body concentric peak power ($W.kg^{-1}$)	0.77	Appropriate (65%) *	Enhancement	Decline ** (-7%)	Inaccurate
Hip concentric rate of power development ($W.kg^{-1}.s^{-1}$)	0.73	Appropriate (92%) *	Enhancement	No change (-2%)	Inaccurate
Hip concentric peak moment ($Nm.kg^{-1}$)	0.72	No stress (-51%) *	No change	Enhancement ** (+9%)	Inaccurate

* Significant difference CMJ Pre versus DJ pre ($p<0.05$)

** Significant difference CMJ Pre versus CMJ post ($p<0.05$)

Red: PRF negatively correlated with jump height means a smaller magnitude was associated with larger jump heights

† A more flexed ankle at joint reversal (indicating a greater ROM) was associated with larger jump heights

Table A11 continued overleaf

Table A11 (Continued) The acute pre-training stress experienced by, and post-training magnitude changes in, subject K's CMJ PRFs

	A	**B**	**C**	**D**	**E**
CMJ PRFs	r	Acute pre-training stress (% diff CMJ vs DJ)	Expected training effect	Post-training change (% change)	Accuracy of expected training effect
Hip moment at joint reversal (Nm.kg^{-1})	0.71	No stress (-4%)	No change	Enhancement ** (+12%)	Inaccurate
Ankle concentric work done (J.kg^{-1})	0.71	Appropriate (35%) *	Enhancement	Decline ** (-10%)	Inaccurate
Ankle concentric peak power (W. Kg^{-1})	0.71	Appropriate (71%) *	Enhancement	Decline ** (-14%)	Inaccurate
Whole body concentric rate of power development (W.kg^{-1}.s^{-1})	0.63	Appropriate (1062%) *	Enhancement	No change (+3%)	Inaccurate

* Significant difference CMJ Pre versus DJ pre ($p<0.05$)

** Significant difference CMJ Pre versus CMJ post ($p<0.05$)

Red: PRF negatively correlated with jump height means a smaller magnitude was associated with larger jump heights

Subject L: Significant 6cm (11%) post-training decrease in CMJ jump height.

Table A12 The acute pre-training stress experienced by, and post-training magnitude changes in, subject L's CMJ PRFs

	A	**B**	**C**	**D**	**E**
CMJ PRFs	r	Acute pre-training stress (% diff CMJ vs DJ)	Expected training effect	Post-training change (% change)	Accuracy of expected training effect
Hip concentric peak moment (Nm.kg^{-1})	0.81	No stress (-6%)	No change	No change (+5%)	Accurate
Whole body concentric work done (J.kg^{-1})	0.79	No stress (-19%) *	No change	Decline ** (-21%)	Inaccurate
Whole body eccentric work done (J.kg^{-1})	0.78	Appropriate (26%) *	Enhancement	Decline ** (-34%)	Inaccurate
Hip concentric work done (J.kg^{-1})	0.74	No stress (-44%) *	No change	Decline ** (-34%)	Inaccurate
Hip eccentric work done (J.kg^{-1})	0.67	No stress (-48%) *	No change	Decline ** (-38%)	Inaccurate
Hip angle at joint reversal (deg) †	-0.65	Inappropriate (97%) *	Decline	Decline ** (+81%)	Accurate
Hip concentric peak power (W. Kg^{-1})	0.64	No stress (7%)	No change	No change (-1%)	Accurate

* Significant difference CMJ Pre versus DJ pre ($p<0.05$)
** Significant difference CMJ Pre versus CMJ post ($p<0.05$)
Red: PRF negatively correlated with jump height means a smaller magnitude was associated with larger jump heights
† A more flexed hip at joint reversal (indicating a greater ROM) was associated with larger jump heights

Table A12 Continued overleaf

Table A12 (Continued) The acute pre-training stress experienced by, and post-training magnitude changes in, subject L's CMJ PRFs

	A	B	C	D	E
CMJ PRFs	r	Acute pre-training stress (% diff CMJ vs DJ)	Expected training effect	Post-training change (% change)	Accuracy of expected training effect
Hip moment at joint reversal (Nm.kg^{-1})	0.58	Appropriate (27%) *	Enhancement	Decline** (-13%)	Inaccurate
Vertical ground reaction force at the low point of the bodies COM (N.kg^{-1})	0.58	Appropriate (98%) *	Enhancement	No change (+3%)	Inaccurate
Amplitude of the centre of mass (cm)	0.55	Inappropriate (-44%) *	Decline	Decline ** (-37%)	Accurate
Ankle angle at joint reversal (deg) †	-0.55	No stress (4%)	No change	Decline ** (+3%)	Inaccurate

* Significant difference CMJ Pre versus DJ pre ($p<0.05$)

** Significant difference CMJ Pre versus CMJ post ($p<0.05$)

Red: PRF negatively correlated with jump height means a smaller magnitude was associated with larger jump heights

† A more flexed ankle at joint reversal (indicating a greater ROM) was associated with larger jump heights

Subject M: Significant 5cm (10%) post-training decrease in CMJ jump height

Table A13 The acute pre-training stress experienced by, and post-training magnitude changes in, subject M's CMJ PRFs

	A	B	C	D	E
CMJ PRFs	r	Acute pre-training stress (% diff CMJ vs DJ)	Expected training effect	Post-training change (% change)	Accuracy of expected training effect
Knee eccentric stiffness ($N.kg^{-1}.m^{-1}$)	0.56	Appropriate (518%) *	Enhancement	Enhancement ** (+11%)	Accurate
Ankle concentric work done ($J.kg^{-1}$)	0.54	No stress (10%)	No change	Enhancement ** (+18%)	Inaccurate
Whole body concentric work done ($J.kg^{-1}$)	0.53	No stress (-25%) *	No change	Decline ** (-6%)	Inaccurate
Whole body eccentric peak vertical velocity ($m.s^{-1}$)	0.53	Appropriate (189%) *	Enhancement	Enhancement ** (+10%)	Accurate
Hip concentric peak power ($W. kg^{-1}$)	0.51	No stress (-21%) *	No change	Enhancement** (+6%)	Inaccurate

* Significant difference CMJ Pre versus DJ pre ($p<0.05$)

** Significant difference CMJ Pre versus CMJ post ($p<0.05$)

Subject N: Significant 5cm (9%) post-training decrease in CMJ jump height.

Table A14 The acute pre-training stress experienced by, and post-training magnitude changes in, subject N's CMJ PRFs

	A	B	C	D	E
CMJ PRFs	r	Acute pre-training stress (% diff CMJ vs DJ)	Expected training effect	Post-training change (% change)	Accuracy of expected training effect
Time between peak power and takeoff (ms)	-0.90	Inappropriate (9%) *	Decline	Decline ** (+11%)	Accurate
Time between joint reversal at the hip and knee (ms)	-0.64	Appropriate (-93%) *	Enhancement	No change (0%)	Inaccurate
Hip concentric peak power (W. Kg^{-1})	0.53	No stress (-31%) *	No change	Decline ** (-21%)	Inaccurate

*   Significant difference CMJ Pre versus DJ pre ($p<0.05$)
** Significant difference CMJ Pre versus CMJ post ($p<0.05$)
Red: PRF negatively correlated with jump height means a smaller magnitude was associated with larger jump heights

Subject O: Significant 3cm (6%) post-training decrease in CMJ jump height.

Table A15 The acute pre-training stress experienced by, and post-training magnitude changes in, subject O's CMJ PRFs

	A	**B**	**C**	**D**	**E**
CMJ PRFs	r	Acute pre-training stress (% diff CMJ vs DJ)	Expected training effect	Post-training change (% change)	Accuracy of expected training effect
Hip concentric work done (J.kg^{-1})	0.82	No stress (-76%) *	No change	No change (+2%)	Accurate
Whole body concentric work done (J.kg^{-1})	0.79	No stress (-31%) *	No change	No change (-1%)	Accurate
Time between peak power and takeoff (ms)	-0.74	No stress (7%)	No change	No change (+4%)	Accurate
Hip eccentric work done (J.kg^{-1})	0.72	No stress (-80%) *	No change	No change (-6%)	Accurate
Hip angle at joint reversal (deg) †	-0.70	Inappropriate (68%) *	Decline	Decline ** (+15%)	Accurate

* Significant difference CMJ Pre versus DJ pre ($p<0.05$)

** Significant difference CMJ Pre versus CMJ post ($p<0.05$)

Red: PRF negatively correlated with jump height means a smaller magnitude was associated with larger jump heights

† A more flexed hip at joint reversal (indicating a greater ROM) was associated with larger jump heights

Table *.* continued overleaf

Table A15 (Continued) The acute pre-training stress experienced by, and post-training magnitude changes in, subject O's CMJ PRFs

	A	B	C	D	E
CMJ PRFs	r	Acute pre-training stress (% diff CMJ vs DJ)	Expected training effect	Post-training change (% change)	Accuracy of expected training effect
Time between peak moment at the knee and ankle (ms)	0.69	Inappropriate (-99%) *	Decline	Decline ** (-60%)	Accurate
Knee eccentric stiffness (N.kg^{-1}.m^{-1})	-0.68	Inappropriate (896%) *	Decline	Decline ** (-18%)	Accurate

* Significant difference CMJ Pre versus DJ pre ($p<0.05$)

** Significant difference CMJ Pre versus CMJ post ($p<0.05$)

Red: PRF negatively correlated with jump height means a smaller magnitude was associated with larger jump heights

Appendix B: Supplemental results from study two

Table B1 Average percentage coefficient of variation for whole body concentric peak power and hip concentric peak power

Individual	Whole body concentric peak power (W.kg^{-1})	Hip concentric peak power (W.kg^{-1})
1	2.6	7.9
2	3.8	12.7
3	2.7	11.8
4	5.0	9.5
5	1.5	7.3
6	4.9	5.7
7	3.2	10.1
8	3.8	5.7
9	4.2	7.4
10	2.7	11.6
11	2.3	6.0
12	1.3	7.5
13	1.8	7.8
14	2.4	7.4
15	2.7	6.0
Mean	3.0	8.3

Appendix C: Supplemental results from study three

Table C1 The post-training change experienced by selected CMJ parameters

	Training group	Control group
1. Concentric phase duration (ms)	8% *	2%
2. Whole body eccentric peak vertical velocity ($m.s^{-1}$)	16% *	0%
3. Knee moment at joint reversal ($Nm.kg^{-1}$)	18% *	-2%
4. Ankle concentric peak power ($W. Kg^{-1}$)	-12% *	2%
5. Ankle concentric rate of power development ($W.kg^{-1}.s^{-1}$)	-16% *	7%
6. Ankle angle at joint reversal (deg)	-1%	4%
7. Knee concentric peak moment ($Nm.kg^{-1}$)	16% *	-6%
8. Knee concentric work done ($J.Kg^{-1}$)	30% *	-6%
9. Knee concentric peak power ($W. Kg^{-1}$)	26% *	-5%

* Significant within group (pre vs. post) and between group (training vs. control) change ($p<0.05$)

Table C2 CMJ parameters whose post-training magnitude change was correlated with CMJ jump height change

CMJ PRFs	Correlation with CMJ height r (p value)
1. Hip concentric peak power (W. Kg^{-1})	0.62 (<0.001) *
2. Whole body concentric work done (J.Kg^{-1})	0.59 (<0.001) *
3. Whole body concentric peak power (W. Kg^{-1})	0.56 (<0.001) *
4. Amplitude of the centre of mass (cm)	0.51 (0.002) *
5. Hip concentric work done (J.kg^{-1})	0.50 (0.002) *
6. Whole body eccentric work done (J.Kg^{-1})	0.49 (0.002) *

* Significant correlation ($p<0.05$)

Table C3 The post-training magnitude change experienced by those CMJ parameters identified as likely CMJ PDFs

CMJ PRFs	Pre CMJ mean (± SD)	Post CMJ mean (± SD)	% Difference
1. Hip concentric peak power (W. Kg^{-1})	20.4 ± 4.1	20.1 ± 3.6	-1
2. Whole body concentric work done (J.Kg^{-1})	7.5 ± 0.7	7.9 ± 0.8	5
3. Whole body concentric peak power (W. Kg^{-1})	49 ± 4	51 ± 5	4 *
4. Amplitude of the centre of mass (cm)	31.7 ± 4.6	35.8 ± 4.2	13 *
5. Whole body eccentric work done (J.Kg^{-1})	3.2 ± 0.5	3.6 ± 0.5	13 *
6. Hip concentric work done (J.kg^{-1})	3.7 ± 0.7	4.0 ± 0.7	6

* Significant within group (pre vs. post) and
between group (training vs. control) change ($p<0.05$)