The use of intra-subject variability as a means of identifying performance enhancement interventions.

By

Gary Park BA, BSc

Supervisor

Dr Kieran Moran

A thesis submitted in fulfilment of the degree of

MSc Biomechanics

October 2005

School of Health and Human Performance, Dublin City University

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of Master of Sceince Degree in Biomechanics is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

Signed: ______________________ ID No.: 91169436

Date: 6/10/2005

Acknowledgements

Firstly, I would like to thank all the subjects that took part in the study, especially those that additionally were part of the pilot work needed

I would like to thank Kieran for his help and patience, for his calmness, understanding and guidance

I extend thanks to Ben and Albert for their input and clarification on technical aspects Thanks also to Neil for his advice and a place to stay on my many trips to the library in Liverpool Thank you to Phil for his help and philosophical advice, putting things in perspective and help in finding a path through problems

Most of all I would like to thank my family Their continued support, patience and understanding over the last few hard years Their love and giving all my life is far beyond anything that could be expected or dreamed of My appreciation for what they have always done for me goes beyond words

Table of Contents

Introductıon 1

1 1 Ratıonal 2

1 2 Hypothesıs 4

1 3 Lımıtatıons 5

Revıew of Lıterature 6

2 0 Introductıon 7

2 1 Varıabılıty 8

2 1 1 Varıabılıty ın movement 8

2 1 2 Movement control theorıes 9

2 1 3 Varıabılıty ın Bıomechanıcs studıes 11

2 1 4 The use of varıabılıty ın movement assessment 14

4 1 5 Group analysıs verses ındıvıdual subject analysıs 18

2 2 Bıomechanıcs of vertıcal jumpıng 20

2 2 1 Vertıcal jump mechanıcs 21

2 2 2 Whole body kınematıcs 22

2 2 3 Whole body Kınetıcs 23

2 2 4 Segmental kınematıcs 27

2 2 5 Segmental kınetıcs 28

2 2 5 Relatıve segmental contrıbutıon 33

2 2 6 Rate of force development (RFD) 35

2 2 7 Enhancement of jump heıght due to countermovement 38

2 2 7 1 Enhancement of mechanıcal varıables 39

2 2 7 2 Possıble mechanısms for enhancement 40

2 3 Coordınatıon 44

2 3 1 Constraınts ınfluencıng movement pattern 45

2 3 2 Bıartıcular muscles 50

2 3 3 Coordınatıon ın Vertıcal jump 51

2 3 3 1 Pattern of joınt extensıon 52

2 3 3 2 Tımıng of peak angular velocıty 54

2 3 3 3 Tımıng of peak joınt power 56

2 3 4 Coordınatıon as a predıctor of jump heıght 57

2 4 Training interventions to increase jump height 58

2 4 1 Training methods to improve neuromuscular capacity 60

2 4 2 Changes in kinetic parameters in drop jumps 62

2 4 2 1 Drop jump technique 63

2 4 2 2 Drop jump height 67

2 4 3 Drop jump training studies 70

Methodology 73

3 1 Subjects 74

3 2 Experimental protocols 74

3 3 Data Acquisition 76

3 4 Data analysis 77

3 5 Variable selection 80

2 6 Statistical analysis 83

Results 84

4 1 Variability and the relationship with jump performance 87

4 1 1 Jump predictors based on group analysis 99

4 1 2 Selection of jump parameter to alter to enhance jump height 100

4 1 3 Variability and parameter identification 102

4 2 Coordination and jump performance 103

4 3 Rate of force development and CMJ performance 105

4 4 Comparisons of kinetics between the CMJ and the DJ 108

Discussion 114

5 1 Inter-subject verses Intra-subject variance 115

5 2 Group analysis 116

5 3 Comparison between group and individual level 119

5 4 Coordination 122

5 5 Inter-subject analysis verses Intra-subject analysis 123

5 7 The use of drop jumps as a means of training the CMJ 130

5 8 The suitability of drop jump as a means of training the CMJ 132

5 9 Conclusion 133

5 10 Future research 134

References 136

Appendix XI

List of Tables

Table 2 1 Coefficient of variance (CV) [%] of initial impact forces in selective landing actions 11

Table 2 2 CV [%] of stride length during running at various running velocities 12

Table 2 3 Inter-subject and intra-subject standard deviation [m] and CV[%] for height attained in the CMJ 12

Table 2 4 CV [%] of duration of concentric phase in the CMJ 13

Table 2 5 Inter-subject CV[%] of segmental data for the CMJ (van Soest et al, 1985) 13

Table 2 6 Inter-subject CV [%] for joint moment and power in the CMJ 13

Table 2 7 Duration of the eccentric and concentric phases of the CMJ 23

Table 2 8 Average whole body vGRF and vertical impulse during concentric phase of the CMJ 23

Table 2 9 Peak vGRF during vertical jumping 25

Table 2 10 Total work done during the concentric phase 26

Table 2 11 Peak joint angle during vertical jump 28

Table 2 12 Peak angular velocity of joints during concentric phase 28

Table 2 13 Peak joint moments during concentric phase of CMJ 29

Table 2 14 Joint moments at time of joint reversal in the CMJ 31

Table 2 15 Peak joint power during concentric phase of the CMJ 31

Table 2 16 Absolute amount of work performed by the joints during the concentric phase in the CMJ 33

Table 2 17 Relative contribution of each joint to total work during concentric phase of the CMJ 34

Table 2 18 Timing of joint reversal to take-off (absolute and relative to total duration) 52

Table 2 19 Mean timing of peak joint velocities (absolute and relative to total duration) 55

Table 2 20 Mean timing of peak joint power prior to take-off (absolute and relative to total duration) 56

Table 2 21 Comparison of whole body concentric phase parameters between CMJ and DJ for the two groups in the study by Bobbert et al (1986a) study and the three conditions in Bobbert et al (1987a) 63

Table 2 22 Kinematic and kinetic output of CMJ and DJ (Bobbert et al, 1986a) 64

Table 2 23 Mean kinematic and kinetic variables from CMJ and DJ (20cm) 66

(from Bobbert et al, 1987a) 66

Table 2 24 Effect of drop jump training on CMJ performance 71

Table 3 1 Cut off frequencies of each joint marker (Moran, 1998) 77

Table 4 1 Mean and variance values of whole body kinematics and kinetics for the group and average variance for individuals during the eccentric phase 87

Table 4 2 Correlation (r) and level of significance (p) for the relationship between jump height and whole body kinematics and kinetics during the eccentric phase 88

Table 4 3 Mean and variance values of joint kinematics and kinetics during the eccentric phase for the group and average variance for individuals 89

Table 4 4 Correlation (r) and level of significance (p) for the relationship between jump height and selected segmental parameters during eccentric phase 90

Table 4 5 Mean and variance values of whole body and segmental kinematics and kinetics for the group and average variance for individuals at the start of the concentric phase 91

Table 4 6 Correlation (r) and level of significance (p) for the relationship between jump height and kinematic variables at the start of the concentric phase 93

Table 4 7 Group mean, SD and CV and individual SD and CV for whole body kinematics and kinetics for during the concentric phase 94

Table 4 8 Correlation (r) and level of significance (p) between jump height and whole body kinematics and kinetics during the concentric phase 95

Table 4 9 Mean and variance of segmental kinematics and kinetic for group and average variance for individuals during the concentric phase 95

Table 4 10 Correlation (r) and level of significance (p) between jump height and segmental kinematics and kinetics during the concentric phase 97

Table 4 11 Percentage of total work done by each joint and correlation with jump height 98

Table 4 12 Descriptions of relationship between jump height and mechanical parameters that where correlated at a group level and number of individuals that also exhibited a correlation with jump height for these parameters 99

Table 4 13 Mean, variance and slope for selected parameters to highlight issue regarding selection parameters to altering to achieve increases in jump height 101

Table 4 14 Mean, standard deviation and range of jump height observed for each individuals and the number of significant relationships observed 102

Table 4 15 Mean timing of joint pairings for key events and measures of inter-subject and intra-subject variability 103

Table 4 16 Mean and variance values of RFD of ankle, knee and hip joint moments, and whole body vGRF . 105

Table 4 17 Correlation (r) between jump height and (i) rate of force development and (ii) power development over selected intervals 107

Table 4 18 Differences in jump height achieved and whole body kinematics and kinetics between CMJ and DJ from 0 3m and 0 5m 109

Table 4 19 Differences in joint kinetics between CMJ and DJ from 0 3m and 0 5m 111

Table 4 20 Kinetic parameters overloaded in the DJ compared to the CMJ, with parameters significantly correlated with jump height in CMJ indicated 113

Table 5 1 Representation of possible scenarios between group and individual analysis . 125

List of Figures

Figure 2 1 Stick diagram with vertical ground reaction force (vGRF) trace overlaid for a) squat jump (SJ), b) countermovement jump (CMJ) and c) drop jump (DJ) **20**

Figure 2 2 Quantitive measures of total force used by Dowling and Vamos (1993) **24**

Figure 2 3 Geometrical configurations of typical segment **48**

Figure 2 4 Isometric force-time curve indicating maximal strength, maximal RFD following three types of training program (Newton R U from www innervations com) **61**

Figure 3 1 Diagram of experimental set-up **75**

Figure 3 2 Diagram for body segments and angle conventions **78**

Figure 3 3 Free body diagram for generic body segment **79**

Figure 3 4 Measures of rate of force development **82**

Figure 4 1 Joint time histories for a representative subject **86**

Figure 5 1 Possible relationships between jump height and a mechanical parameter **125**

Figure 5 2 Interaction of variability and slope of relationship between jump height (y axis) and a mechanical jump parameter (x axis) **129**

Abbreviations

1 RM	one repetition maximum
BCOM	whole body centre of mass
$BCOM_{s\ to}$	rise in the BCOM from standing to take-off
BDJ	bounce drop jump
BW	body weight
CDJ	counter drop jump
CMJ	countermovement jump
COM	centre of mass
CV	Coefficient of variability
DJ	drop jump
DJ30	drop jump from 30cm platform
DJ50	drop jump 50cm platform
DJ-H	drop jump for maximise rebound height
DJ-H/t	drop jump for combination of rebound height and minimum duration
FT	fast twitch muscle fibres
G b	group analysis based on the highest jump of the 15 jumps undertaken
G m	group analysis based on the mean value of the 15 jumps undertaken
HAT	head-arms-trunk body segment
JR	joint reversal
MV	peak angular velocity
RFD	rate of force development
ROM	range of motion
RPD	rate of joint power development
SD	standard deviation
SJ	squat jump
SSC	stretch-shorten cycle
ST	slow twitch muscle fibres
TO	take-off
vGRF	vertical ground reaction force
VJP	vertical jump performance

The use of intra-subject variability as a means of identifying performance enhancement interventions - Gary F Park

Background The most common method used to identify performance determining biomechanical factors has been to compare differences between individuals This group analysis approach assumes that the movement strategy for all individuals is the same However, not every athlete has the same neuromuscular capacity, anthropometrics and muscle morphology It may be more appropriate to make inferences about an individual's movement strategy by treating each individual as their own experiment group, examining differences between repetitions of an individual's own performance, referred to as individual analysis The aim of the study is to identify the performance determining biomechanical factors of countermovement vertical jumping, at both a group level and individual level and to highlight the commonality and differences between the two approaches The study also aims to determine whether drop jumps (DJs) overload the performance driving kinetic factors of the countermovement jump (CMJ), thereby assessing the appropriateness of DJs as a training method

Experiment Eighteen male university students performed 15 countermovement jumps (CMJ), 15 drop jumps from 0 30m (DJ30) and 15 from 0 50m (DJ50) From ground reaction force and motion data, kinematic, kinetic and coordination parameters were calculated for the whole body, hip, knee and ankle Correlation analysis was used to identify the biomechanical factors that may explain differences in jump height achieved, both between individuals (inter-subject) and within repetitions of an individual (intra-subject) Differences in kinetic factors between the CMJ, the DJ30 and the DJ50 at a group level was assessed using a two-way repeated measures ANOVA, and at an individual level using a single subject repeated measures ANOVA

Results A number of biomechanical factors were found to be significantly correlated with CMJ height at a group level These however, were not always correlated at the individual level, and visa versa Opposing relationships were evident at the individual level, both between individuals and compared to the group analysis Knee kinetic parameters were significantly greater in the DJ than the CMJ at a group level and for the majority of subjects at an individual level In contrast, both ankle and hip kinetics were not overloaded in the DJ at the group level, although an overload of ankle kinetic parameters was achieved by a number of individuals

Conclusion Results from a group and individual analysis are not always comparable A considerable amount of important information may be lost regarding individual performance strategies when only a group analysis is employed However, the use of solely an individual analysis based approach would not reveal any performance factors relating to differences between subjects, and a case for a group based analysis to be used to supplement an individual analysis therefore exist Knee kinetic factors were overloaded in the DJ compared to the CMJ, while hip kinetics factors were not and the overload of ankle kinetic factors was found to be dependent on the DJ technique employed

Key words vertical jump performance, countermovement jump, drop jump, intra-subject variability, individualised technique, rate of force development

Introduction

1 1 Rational

Endeavours to continually improve an athlete's performance rely on structured, progressive training programs, encompassing enhancement of both movement technique and neuromuscular output capacity Athletes and coaches seek to determine which factors determine performance success and which training exercise protocols can be utilised to develop these factors Methods of identifying performance driving or performance limiting factors have predominantly focused on group based analyse, either citing the performance strategy of elite athletes as the 'gold standard' to which individuals should aspire (Hay, 1995), or identifying differences between individuals (Dowling and Vamos, 1993) This de-emphasises the importance of the individual and pertains to an "abstract" or "average" optimal movement strategy that can be applied to all individuals (Dufek et al, 1995) However, not every individual has the same neuromuscular capacity (e g individual joint power, rate of power production and joint dominance), anthropometrics (e g limb length and relative mass) and muscle morphology (e g percentage muscle fibre type) The unique physical characteristics of individuals, coupled with the multi-functional degrees of freedom associated with the human body, means that there are a large number of possible movement strategies Dufek and Zhang (1996) found a model formulated to explain forces upon landing from a jump, using the group approach, was suitable for some individuals but not for all This approach would be valid if everyone was identical Therefore, it may be inappropriate to assume one optimal movement strategy to be suitable for all It may be more appropriate to identify an optimum performance strategy for an individual based on differences between repetitions of the individual's own performance If this principle is accepted, it follows that the individual should be the focus of examinations While this may not be appropriate for all individuals, it may be for elite level performers where minor refinements of technique are sought and any deviation between what is required to increase performance for the individual and what was required for the group as a whole might be unacceptable (Bates, 1996, Hopkins, 1985) By studying each individual separately, the differences in physical characteristics are controlled and any change in performance must be due to the movement strategy employed A second problem with a group based analysis is that, if different movement strategies exist between individuals, it is possible that they may numerically cancel out each other at the group level, resulting in neither strategies being identified as important

In the present study the CMJ was selected as a model to examine and compare group and individual based biomechanical analysis This was because it is a relatively simple and well-learnt task where performance is clearly and objectively defined In addition, it is evident in many sporting activities The existence of individual performance strategies in vertical jumping is evident in the literature (Aragon-Vargas and Gross, 1997b, Hubley & Wells, 1983, Jensen et al, 1991), but only one study compared the results of both a group and individual analysis (Aragon-Vargas and Gross, 1997a, 1997b) This study used multiple regression as the statistical method to identify factors related to vertical jump performance When the sole objective is the formulation of a model for prediction, multiple regression is suitable However, with multiple regression the potential exists of the exclusion of relevant variables or inclusion of an erroneous relationship between a variable and jump height Therefore, multiple regression may not be the best approach for the identification of biomechanical parameters that determine jump height and the results of studies using multiple regression must be viewed with caution Instead, the present study used bivariate correlation analysis to examine the relationship between each parameter and jump height

The height achieved in vertical jumping is not simply dependant on the movement technique employed but also the neuromuscular system's capacity to produce force (Tomioka et al, 2001, Walshe et al, 1998) The neuromuscular output capacity is improved through a progressive overload, using actions that conform well with the target movement in respect to the muscle groups used, the coordination pattern, the joint range of motion (ROM), the velocity of contraction and the muscle action employed (Bobbert, 1990) One such training intervention, which has been extensively employed, purportedly providing effective overload, is the drop jump (DJ) However, there are contrasting findings from studies regarding the extent, if any, of an enhancement in the CMJ following DJ training programs (Blatter and Noble, 1979, Brown et al, 1986, Matavuji et al, 2001) This may be due to differences between individuals' technique For some individuals the joint kinetics may be overloaded in the DJ compared to the CMJ, while in others no change or a reduction in joint kinetics may be evident Additionally, the kinetic parameters that are overloaded in the DJ may not be kinetic parameters that require to be trained for improvements in jump height To date no study appears to have determined if drop jumps overloads the factors related to CMJ performance at an individual level

Therefore the aims of the present study were to -

(i) Identify the biomechanical factors that correlate with jump performance, at both a group and an individual level

(ii) To identify the kinetic factors that are overloaded in the DJ, at both the group and the individual level

(iii) To assess whether the biomechanical (kinetic) factors correlated with jump height in the CMJ are overloaded in the DJ

(iv) To determine if the kinetic parameters are overloaded more in the DJ50 than the DJ30

(v) To examine the extent to which the results of a group and an individual analysis are comparable, both for factors that correlate with jump height and differences in jump conditions

1 2 Hypothesis

The biomechanical factors that relate to differences in CMJ height at an individual level of analysis do not always match those at a group level of analysis

A number of joint kinetic parameters are greater in the DJ than the CMJ at both the group level and the individual level of analysis

A number of joint kinetic parameters are greater in the DJ50 than the DJ30 at both the group level and the individual level of analysis

The performance determining (kinetic) factors of the CMJ are overloaded in the DJ

1 3 Limitations

Correlation measures the extent to which two parameters vary in relation to each other It does not signify that the change in one parameter <u>causes</u> the change in the other The precise relationship must be established through systematically altering the biomechanical parameter while monitoring changes in the jump height achieved However, for the purposes of discussion in the present study, the theoretical implications of a causal relationship, which mirrors the findings of the correlation analysis, will be additionally discussed Bivariate correlation analysis only reveals linear patterns, the possibility exists that a non-linear pattern may be present Visual examination of scatter plots of each variable and jump height was undertaken Where a non-linear pattern was suspected, the residuals were plotted against the expected values from bivariate regression analysis, and the pattern was examined (Montgomery, 1991) No non-linear patterns were observed for any variable

Limited instruction was given in regards to jump technique during the course of the experiment, so as not to influence the strategy employed The movement technique employed in the DJ has been shown to influence the overload of joint kinetics compared to the CMJ (Bobbert et al, 1987a) Further instruction may have enabled great overload of joint kinetics, however, it was the response relating to the freely chosen movement strategy that was of interest

Review of Literature

2 0 Introduction

In all facets of human movement no two attempts of the same movement action result in exactly the same movement kinematics, kinetics or performance outcome Performance outcomes lie somewhere on a continuous spectrum from worst performance to best, it is the essence of sports performance to strive for the later Endeavours to continually reach and surpass the athlete's best performance rely on structured, progressive, training programs encompassing enhancement of both neuromuscular output capacity and movement technique Identification of which aspect of technique should be trained to enhance performance has traditionally been based on identifying differences between individuals (Dowling and Vamos, 1993), often using performances of elite athletes as the 'gold standard' to which individuals should aspire (Hay, 1995) However, individuals differ in their neuromuscular capacity (e g individual joint power, rate of power production and joint dominance) their anthropometrics (e g limb length and relative mass) and their muscle morphology (e g percentage muscle fibre type) Therefore, it may be inappropriate to expect one technique to be suitable for all and it may be more appropriate to tailor training programs based on differences between repetitions of an individual's own performance Similarly, in attempting to improve a specific neuromuscular component (e g knee joint power), differences may exist between individuals as to the extent the component is overloaded when different exercises are employed (e g drop jump from 30cm vs weighted vertical jumps vs drop jump from 60cm) Again it may not be appropriate to expect one training exercise to be suitable for all

This review will examine how variability has been viewed in biomechanical and motor control literature and the role it plays in optimising movement strategy from a dynamic systems approach The case for a single subject analysis approach will be put forward and the observed magnitudes of both inter- and intra- subject variability in the biomechanical literature will be outlined The use and misuse of variability in biomechanical studies to reveal mechanisms of performance enhancement will be briefly highlighted, with particular reference to multiple regression analysis

The vertical jump is evident in many sporting activities and has been used as a research model in numerous biomechanical studies (Bobbert et al, 1987a, Jensen and

Phillips, 1991, van Ingen Schenau et al, 1987) due to it being a relatively simple and well learnt task, where maximum performance is clearly and objectively defined (Aragon-Vargas and Gross, 1997a) Vertical jumping outcome (i e jump height), is the combined result of the magnitude of mechanical output of the neuromuscular system and the coordination pattern (technique) employed This review will outline the biomechanical variables that have been examined in the study of vertical jumping and their relationship to jump height, along with a review of studies that have sought to investigate the coordination pattern employed

Finally, training methods employed to improve vertical jump performance will be examined, with a particular emphasis on drop jumping (DJ) How changes in the DJ technique or drop height can affect the magnitude of kinetic parameters will be examined Finally, a brief outline of results of training studies utilising the DJ will be detailed

2 1 Variability

This section will introduce the idea of variance and will briefly outline the various theories of movement control, which have been forwarded in the motor control literature The case will be put forward for viewing the control of the human body as a dynamic system and examine the role variability plays in shaping movement pattern formation The amount of variability observed in the biomechanical analysis of a variety of movements will be given, both between subjects (inter-subject) and within repeated performances by an individual (intra-subject) Statistical methods, which utilise variance as a means of identifying trends in the data, will be briefly evaluated, outlining their merits and limitations

2 1 1 Variability in movement

Several attempts to solve the same motor task will inevitably lead to different patterns of movement actions, including kinematic, kinetic, muscle activation (Latash et al, 2002) and movement outcome Bernstein (1967) referred to this as 'repetition without repetition', meaning each repetition involves a unique, nonrepetitive movement pattern (Latash et al, 2002) This tendency for repetitions to differ from each other is referred to as variability (Orr, 1995) and is a natural occurring phenomenon associated with all types of human movement (DeVita & Bates, 1988) Variability within an individual's performances is referred to as intra-subject variability (Aragon-Vargas & Gross, 1997a & b, DeVita & Skelly, 1990) or within-subject variability (Borzelli et al, 1999, Heiderscheit, 2000), while variability between individuals is referred to as inter-subject variability (Aragon-Vargas & Gross, 1997a & b, Borzelli et al, 1999) or between-subject variability (Hopkins et al, 1999) In spite of the widespread evidence of variability in movement, it has not been given the same theoretical and operational significance that invariance has procured, based on the belief that consistency of response is indicative of a motor strategy

2 1 2 Movement control theories

Some theories of motor control have long proposed that movement is controlled by centrally stored patterns (or prescriptions), which function with little or no sensory input during completion of the task (Gentner, 1987) This suggests that for each possible movement-environment combination a separate motor program must exist However, this would lead to immense memory storage requirements In acknowledgement of this limitation, Schmidt (1975) forwarded the notion of a generalised motor program for a given class of movement, rather than each specific movement These generalised motor programs present pre-structured commands for a number of movements, which can be adjusted for velocity and force requirements when specific response parameters are provided (Schmidt, 1975) Relative timing invariance in the kinematics of movement has been cited as evidence to support the generalised motor program theory (Schmidt, 1985) However, a number of authors have clearly shown that timing invariance is not apparent in many movements (Burgess-Limerick et al, 1992, Genter, 1987, Maraj et al, 1993) and the procedures used previously to support the general motor program were inappropriately applied (Gentner, 1987)

Over the last three decades there has been substantial work by ecological psychologists rejecting the idea of invariance in favour of a the concept of functional variability The introduction of concepts and methods of nonlinear dynamics and chaos theory has led to the interpretation of movement variability as more than merely noise but as being necessary for movement pattern optimisation and driven by a deterministic process It has been suggested that the problem of movement pattern selection and production can be resolved by conceptualising the human movement system as a complex dynamic system (Clark et al, 1989, Diedrich and Warren, 1995, Newell and Slifkin, 1998, Stergiou et al, 2001) Complex systems such as the human body exhibit many fundamental attributes, including many degrees of freedom which are free to vary, many different interacting levels of the system (neural, perceptual and muscular-skeletal), non-linear output and the capacity for stable and unstable patterns as it spontaneously shifts between coordination states through processes of self-organisation (David et al, 2000)

Complex systems are seen as open non-conservative systems with variable amounts of kinetic energy dissipated around its components at any given moment The energy already in the system interacts with instantaneously available forces in the environment, such as reactive forces and gravity The energy entering the system can interact with energy already within the system to produce chaotic and unpredictable effects on the system However, there appears to be a surprising amount of stability within the systems, suggesting that processes of self-organisation are present which maintain the stability

From a dynamic systems viewpoint, movement pattern formation is the result of the self-organisation of the neuromusculoskeletal system confronted with the specific dynamic constraints of the task and environment, as opposed to spatio-temporal prescriptions from a hierarchical control system (Temprado et al, 1997) Variability in the system should not be considered merely as noise but predominantly as a functional property, which allows the system to explore new movement patterns From this perspective variability can be viewed as an index of fluctuation necessary to allow the movement system to adapt to changing constraints from one situation to the next (Button et al, 2003) Given the functional nature of variability, higher levels of variability in certain parameters may be indicative of a highly skilled adaptation to task constraints, rather than merely a reflection of motor system noise (Davids et al, 2000) Clearly, since variability may be the result of the system exploring new movement patterns, variability may provide a window for the identification of optimum movement patterns

2 1 3 Variability in Biomechanics studies

Variability, both inter-subject and intra-subject, is evident in all movements Tables 2 1 to 2 6 detail examples of both inter-subject and intra-subject variability reported for biomechanical parameters for gross motor tasks Table 2 1 and table 2 2 report magnitudes of variability experienced in a variety of movements, while tables 2 3 to table 2 6 specifically detail jumping tasks Table 2 1 examines the initial impact peak forces for a variety of landing actions The ratio of intra-subject variability to inter-subject variability ranges from approximately half (Dufek et al, 1995) to comparable magnitudes (Dufek and Bates, 1990, Lees and Bouracier, 1994)

Table 2 1 Coefficient of variance (CV) [%] of initial impact forces in selective landing actions

Study	Inter	Intra Mean	Intra Range
	Running		
Stergiou et al (2001)	12 6		
Lees & Bouracier (1994)	9 1	9 3	5 5 - 14 1
Miller (1990)	12 1		
Dufek et al (1995)	20 9	8 8	6 3 - 10 5
	Walking		
Hamill & McNiven (1990)	5 3		
Hamill et al (1984)	9 3		
	Landing from vertical drop (60cm)		
Dufek & Bates (1990)	14 3	29 1	23 6 – 33 1
Dufek & Bates (1991)	25 9		
Dufek et al (1995)	26 9	14 0	8 31 – 23 2

A considerable amount of variability exists in the kinetics of movement both inter-subject and intra-subject Lees and Bouracier (1994) found the average intra-subject coefficient of variability (CV) for vertical impact force to be approximately the same magnitude as the inter-subject CV However, individual levels of intra-subject CV ranged from 60 4% to 154 9 % of the inter-subject CV observed At a segmental level, DeVita and Skelly (1990) found the intra-subject CV for joint moments to be 58%, 44% and 47% of the inter-subject variation for hip, knee and joint moments, respectively, during the support phase of running

Table 2 2 CV [%] of stride length during running at various running velocities

Study		2 5m/s	3m/s	3 5m/s	4m/s
	Inter	4 6	4 5	12 2	
Craib et al (1994)	Intra	2 5	2 2	2 3	
		1 3-3 3	1 7-3 3	1 2-4 3	
Cavanagh & Kram (1989)	Inter		5 7	5 9	5 6
Heiderscheit et al (2002)	Inter	6 1			
Schieb (1986)	Inter				7 0

Note Velocities have been reported to nearest 0 5m/s
Average and range of individuals intra-subject variability is outlined for Craib et al (1994)

Table 2 2 shows the magnitude of inter-subject variability in stride length during running at selected velocities Intra-subject variability is also detailed for Craib et al (1994), where similar percentages of intra-subject CV to inter-subject CV of stride length for running velocities of 2 7m/s and 3 1 m/s were found (54% and 49% respectively) At a higher velocity of 3 5m/s the intra-subject CV was relatively smaller compared with inter-subject CV This can be attributed to a greater range of stride lengths chosen by individuals at the higher velocity, thus increasing inter-subject variance Since the individual CV of stride length did not significantly differ across velocities, the reduction in the percentage can be attributed to a change in inter-subject variance alone No data for intra-subject variability was reported for the other studies

Table 2 3 outlines the inter-subject CV for vertical jump height achieved in the countermovement jump (CMJ) Additionally, intra-subject data for Aragon-Vargas & Gross (1997b) is reported, which is of a reduced magnitude compared to inter-subject variability

Table 2 3 Inter-subject and intra-subject standard deviation [m] and CV[%] for height attained in the CMJ

Study	number of subjects	variance type	SD	CV
Aragon-Vargas & Gross (1997a)	52	Inter	0 070	13 4
Aragon-Vargas & Gross (1997b)	50 trials	Intra	0 013	3 1
Dowling & Vamos (1993)	97	Inter	0 101	34 0
Jaric et al (1989)	39	Inter	0 050	13 2
Robertson & Fleming (1987)	6	Inter	0 850	17 0
Rodacki et al (2001)	20	Inter	0 044	13 2
Nagano et al (1998)	6	Inter	0 018	5 2
Van Soest et al (1985)	10	Inter	0 060	11 1

Variability in the duration of the concentric phase in the CMJ is shown in table 2 4 as an example of temporal variability for a jumping task Only one study could be found that detailed both inter- and intra-subject variability (Aragon-Vargas & Gross, 1997a, 1997b) As with the height attained in the CMJ outlined in table 2 3, inter-subject variability is greater than intra-subject variability

Table 2 4 CV [%] of duration of concentric phase in the CMJ

Study	Inter	Mean Intra	Range Intra
Aragon-Vargas & Gross (1997)	19 6	6 4	5 6-6 8
Jaric et al (1989)	19 2		
Rodacki et al (2001)	14 4		
Van Soest et al (1985)	15 85		

Table 2 5 details inter-subject variability observed in a single study by Van Soest et al (1985) for joint kinematic and kinetic parameters in the CMJ Comparisons can be made across variables as each was produced from the sample group Lower variability was observed for the joint angle data (kinematic measure) than moment, power and work data (kinetic measure) There does not appear to be a difference between the joints in terms of the magnitude of variability This is supported in general, in analysis of joint moment and power data for the CMJ (table 2 6)

Table 2 5 Inter-subject CV[%] of segmental data for the CMJ (van Soest et al, 1985)

	Hip	Knee	Ankle
Angle @ JR	16 13	17 39	9 91
Peak Moment	16 25	18 39	16 90
Peak Power	23 47	21 06	26 53
% Work	18 23	22 02	24 15

Note JR = joint reversal (point where angular motion of the joint reverses direction)

Table 2 6 Inter-subject CV [%] for joint moment and power in the CMJ

Study	Joint	Peak moment	Peak Power
Aragon-Vargas & Gross (1997a)	Hip	25 1	28 4
	Knee	35 1	30 1
	Ankle	19 7	29 1
Ravn et al (1999)	Hip	11 5	14 2
	Knee	7 0	9 1
	Ankle	18 3	20 8
Rodano & Roberto (2002)	Hip	21 3	28 3
	Knee	20 0	23 7
	Ankle	14 2	15 8
Van Soest at al (1985)	Hip	16 3	23 5
	Knee	18 4	21 1
	Ankle	16 9	26 5

2 1 4 The use of variability in movement assessment

Human movement performance is dependent on the interaction of numerous biomechanical factors Vertical jump height is predominately determined by the vertical velocity of the body's centre of mass (BCOM) at take-off Whole body vertical velocity in vertical jumping is in part a function of individual joint angular velocities, which in turn are in part dependent on individual joint kinetics Joint kinetics has been seen to vary both between individuals and within repetitions by an individual for vertical jumping (Rodano and Roberto, 2002, Van Soest et al, 1985) Likewise, variability has been observed in performance outcome (table 2 3) As the performance outcome is dependent on a number of biomechanical factors, it seems intuitive to assume the variability in performance outcome may be the result of variability in these underlying joint kinematics and kinetics, and knowledge of how they vary in relation to each other may provide a means of identifying differences in performance

Variance has normally been viewed as a nuisance, requiring additional measurements to obtain a representative value and the use of statistical inference to determine differences However, variance may reveal information about the movement pattern and can be used as a means of analysis Variance with respect to the interrelationship among variables is called covariance and examines the extent to which two sets of variables exhibit similar tendencies to differ (Orr, 1995) Two statistical methods that are based on covariance are correlation and regression

Correlation was first put forward by Galton in 1888 in his paper to The Royal Society of London, referring to it as an "index of co-relation" (Stigler, 1986) Correlation measures the extent to which the variance of one parameter can be explained by the variance of another

An extension of correlation is bivariate linear regression, which involves producing the equation of a line that passes through the data plotted on a Cartesian plane such that the squared deviation of the observed points about the line are minimised Bivariate regression can be simply viewed as a line that best represents the trend in the data However, as the number of parameters increase it becomes difficult to visualise the model of best fit for the data, but formulation of a mathematical model of the relationship is still possible via multiple regression and has been used in a number of biomechanical studies (Aragon-Vargas and Gross, 1997a, Dowling and Vamos, 1993, Dufek et al, 1995, Hay et al, 1978, Tomioka et al, 2001) Multiple regression always explains at least as much variability in the dependant variable as bivariate regression, but the potential of a sample specific relationships increases with the number of variables that are included in the model Clearly it would be beneficial to have a method to reduce the number of variables entering the model The most commonly employed method of variable elimination in biomechanical studies is by stepwise regression (Aragon-Vargas & Gross, 1997a, Dufek et al, 1995, Hay et al, 1978) This can take the form of backwards or forward elimination, resulting in either variables being removed from a model containing all the variables or variables being added to the bivariate model containing the variable most strongly correlated with the dependent variable

Aragon-Vargas and Gross (1997a) used multiple regression to identify the biomechanical factors that distinguish differences in jump height between 52 individuals The three regression models that explained the largest amount of variance in jump height along with the best single variable predictor at both a whole body and segmental level were reported In a subsequent study they examined the biomechanical factors that determined jump height within individuals and selected three subjects to represent the best, worst and average performers (subject B, subject W and subject A, respectively) Factors contained within the regression models of at least two of the three subjects were tested to determine it they significantly related to jump height for a further five subjects

Even though the model obtained with multiple regression may be the best possible for prediction, stepwise regression is pure empirical selection and may not include all theoretically relevant variables One of the biggest problems involved in multiple regression is the predictor variables being correlated with each other, which is referred to as multicollinearity (Grimm & Yarnold, 1995) When multicollinearity is present, variables strongly correlated with each other may not be included together because when one of the variables is already in the model, the inclusion of the other may contribute only a diminished source of explained variance in the dependant variable This may increase the likelihood of inclusion of variables primarily as the result of being uncorrelated with the existing variables in the model and at the expense of variables more strongly related to the dependant variable This was highlighted in the study of vertical jumping by Aragon-Vargas and Gross (1997a) where the amplitude of the BCOM was the best single predictor of jump height for subject A (r = 0 557) but was not included with other variables in the best three multiple regression model

A greater problem occurs when two variables, highly negatively correlated with each other, are included in a regression model together This may result in the coefficient of one variable changing sign to accommodate the other within the model (Hair et al, 1987), thus predicting the opposite relationship the parameter has with the dependant variable This occurred in the group regression models explaining the variation in jump height in Aragon-Vargas and Gross (1997a) Both peak hip moment and hip moment at the point where the joint reverses direction, termed joint reversal (JR), were positively correlated with jump height on their own (r = 0 524 and r = 0 484, respectively), but when included with other variables (models 16 and 17, p36) displayed a negative relationship within the model While this does not cause a problem when the model is used for purely prediction but misleading information may be drawn about the individual relationship a variable has with jump height

Multiple regression analysis is suitable if the sole objective is the formulation of a model for prediction, but when used to gain insight into the effect of various parameters on a dependant variable, monitoring of multicollinearity is critical Of the biomechanical studies mentioned above, only Dufek et al (1995) and Tomioka et al (2001) investigated whether the variables entered into the stepwise process were uncorrelated Aragon-Vargas & Gross (1997a, 1997b) and Dowling and Vamos (1993) in their analysis of vertical jump performance entered a multitude of biomechanical parameters into the stepwise process with no stated consideration given to whether the variables were correlated or uncorrelated In light of the inter-related nature of the human movement system, the assumption of uncorrelated predictor variables is highly likely to have been violated
Aragon-Vargas and Gross (1997a) stated "the purpose of this study was to identify the relevant predictors and not necessarily to build the most accurate model" (p32), after

previously stating, "since most factors proposed as relevant to VJP (vertical jump performance) are interrelated in a complex fashion, a sensible approach to their study is the use of a multiple-regression analysis technique" (p26) In light of their aim, instead of rejecting multiple regression due to the potential effects posed by multicollinearity, which they acknowledge may be present, they utilised a technique that has the potential for excluding relevant variables from the model This was illustrated by only including the ankle and hip angle at take-off in one model, explaining differences in the vertical height difference of the BCOM between standing and take-off, and the knee angle being included in another model Multiple regression does not allow for the fact that potentially a relevant predictor may not be included in any model due to the inclusion of another factor, nor does it protect against the reversal of the sign of the relationship as highlighted above with respect to peak hip moment and hip moment at JR This makes multiple regression an unsuitable means of identifying relevant factors of jump performance Findings from studies, which use multiple regression with no reference to the degree that predictor variables are correlated, must be viewed with caution

To avoid multicollinearity, the selection of variables that measure the same (or similar) factors must be eliminated To reduce the effect of multicollinearity a number of approaches may be employed including transformation of the data or the use of techniques such as factor analysis (e g principle component analysis) Factor analysis combines individual parameters into new uncorrelated parameters, which can be subsequently used in regression techniques (Freund & Minton, 1979) These new parameters, called factors, form linear combinations of the original parameters Kollias et al (2001) used principle component analysis to investigate the effect of changes in strength and coordination in vertical jumping but did not relate the new factors to changes in performance While satisfying the conditions of regression techniques, these new factors introduce complications in interpretation of the results, as often no meaningful combinations are produced

One way of protecting against these potential pit-falls of multicollinearity, while still gaining insight into the mechanics of performance enhancement, is to examine the relationship between each parameter and changes in the performance outcome individually by means of bivariate correlation analysis This approach has been used in a number of biomechanical studies (Dowling and Vamos, 1993, Harman et al, 1990, Jaric et al, 1989)

4 1 5 Group analysis verses individual subject analysis

The group approach to technique analysis presumes that a single, 'abstract' optimal movement strategy exists and it can be applied to all individuals This would be true if everyone was physically identical However, individuals differ in their neuromuscular capacity (e g individual joint power, rate of power production and joint dominance) their anthropometrics (e g limb length and relative mass) and their muscle morphology (e g percentage muscle fibre type, angle of muscle pennation) The unique physical characteristics of individuals, coupled with the multi-functional degrees of freedom associated with the human body, allow the possibility of diverse movement strategies to exist A strategy is a neuromusculoskeletal solution for a given performance task, resulting in a unique pattern of movement and variability due to biomechanical, morphological and environmental constraints (Bates, 1996) Evidence of individual strategies is abundant in the literature for jumping (Aragon-Vargas and Gross, 1997b, Jensen and Phillips, 1991, Rodacki et al, 2002), landing (Lees, 1981, Dufek and Bates, 1991, Dufek and Zhang, 1996, Dufek et al, 1995) and running (Dufek et al, 1995, Lees and Bouracier, 1994)

Dufek and Bates (1991) assessed the impact properties of four types of sports and found the impact forces across subjects did not follow a consistent trend for all shoe conditions While one shoe was determined as the best for the group the same shoe was not best for all individuals within the group Lees (1981) also found variation in landing pattern between subjects and analysed in detail the two extreme cases, hard and soft landings Dufek et al (1995) also found different landing strategies for individuals Lees and Bouracier (1994) while investigating the shock absorbing characteristics of individuals during running found differences in the braking force between experienced and non-experienced runners Such changes in shock absorbing strategies would potentially obscure the effect of an intervention investigating footwear Jensen and Phillips (1991) in their study of coordination of jumping activity found no constant pattern of joint reversal for all subjects While hip-knee sequencing was stable across jumps for all subjects, only two of the six subjects maintained the sequence of extension between the ankle and knee joint Changes in the pattern of joint reversal between individuals were also observed by Aragon-Vargas and Gross (1997a) and Rodacki et al (2002)

Dufek et al (1995) found that a single mechanical parameter explained variance in both the first and second impact peak experiences during landing at a group level However, only two of the six subjects used the same landing strategy as the group model for the first impact peak and none of the individuals used the group strategy for the second impact peak During running Dufek et al (1995) found none of the six individuals performed like the group average, where a single knee variable explained the variance in the impact peak, instead three distinct strategies of shock attenuation were observed at the individual level, none of which included the group predictor They concluded that the group approach produced a mythical "average" performer, which did little to explain the performance strategies for individual subjects

Aragon-Vargas and Gross (1997a) used multiple regression to identify the biomechanical parameters at both the whole body and joint level that distinguished differences in jump height between 52 individuals and between repetitions of an individuals own movement (Aragon-Vargas and Gross, 1997b) The best whole body predictors of jump height at a group level (peak and average power), were also significant predictors for all individuals examined Amplitude of movement, while present in the prediction models at a group level, was not significant for six of the eight individuals examined At the group level, peak hip power was the best segmental predictor of jump height but at an individual level was only a significant predictor for six of the eight subjects Additionally, while ankle joint kinetics appeared in numerous models of jump height at an individual level, no ankle kinetic parameters appeared in the models at the group level

2 2 Biomechanics of vertical jumping

Numerous biomechanical variables have been examined at the whole body and segmental level in an effort to gain insight into factors that determine vertical jump performance The magnitude of the biomechanical variables and where possible their relationship with jump height observed in these studies are outlined in this section

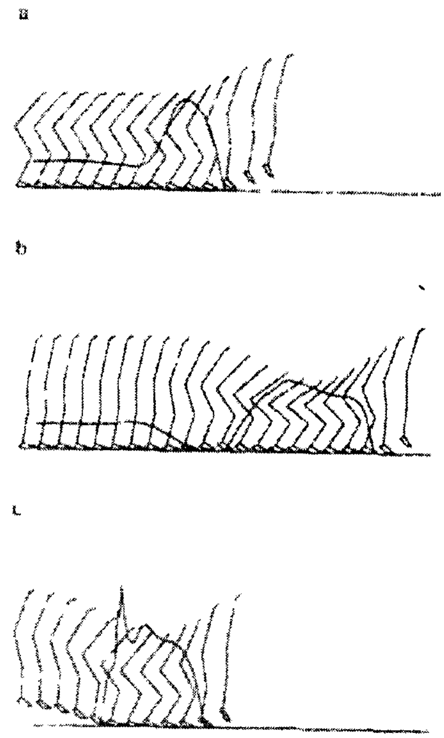


Figure 2 1 Stick diagram with vertical ground reaction force (vGRF) trace overlaid for a) squat jump (SJ), b) countermovement jump (CMJ) and c) drop jump (DJ) (Voigt et al, 1995)

Three types of vertical jump have commonly been used in biomechanical studies, the squat jump (SJ), the countermovement jump (CMJ) and the drop jump (DJ) In the squat jump (SJ) the subject starts from a stationary, semi-squatted position with knees and hip flexed for a few seconds, before vigorously extending causing the BCOM to rise vertically When subjects are asked to jump for maximum height, predominately a countermovement is spontaneously employed (Bobbert, 1990) The countermovement jump (CMJ) starts with the subject in an erect position from which they lower their BCOM quickly, before vigorously rising again as the joints are extended In the DJ increasing the initial height that the BCOM is held above that of standing increases the amount of negative work further The body dropping under the force of gravity starts the DJ and upon landing, a jump for maximum height is performed Drop jumping will be discussed in section 2 4, while section 2 2 and 2 3 will focus primarily on the mechanics of the CMJ

2 2 1 Vertical jump mechanics

Jumping for height is a skill involved in many sporting activities and dance Most healthy individuals can jump and a capacity for jumping is evident from an early age (Clark et al, 1989) Differences in height achieved during jumping are evident both between individuals and within repeated jumps by an individual Numerous possible movement strategies exist and knowledge of which strategy yields the greatest jump height would be of benefit to coaches and athletes in order to guide training programs to maximise jump height Once knowledge of the mechanisms that enhance jump performance is gained, more informed and specific training interventions could be formulated

The aim of vertical jumping is to raise the BCOM as high as possible above the ground This is achieved by exerting a vertical force greater than the weight of the body against the ground by means of the neuromuscular system However, the human body is a multi-task machine, capable of performing many diverse movements and is not only designed to project the body vertically Due to this multi-functionality, the muscles' line of action are not oriented specifically to exert a force directly downwards, thus the body must reorganise itself though a well coordinated series of carefully timed rotations of the various body segments to exert a collective force downwards To achieve this, the body must take into consideration the anatomical constraints the structure of the body imposes in light of additional constraints related to the task

Jump height is determined by vertical velocity of the BCOM at take-off and it's vertical position above the ground at take-off (Dowling & Vamos, 1993, Hay et al, 1978) The relative contribution of the rise of the BCOM above standing height at take-off has been found to be between 25% (Bobbert et al, 1996) and 29% (Harman et al, 1990) of the total height achieved The vertical velocity of the BCOM, is determined by the vertical impulse exerted in excess of that needed to support the mass of the body The vertical impulse in turn is sum of the angular impulses exerted by the individual joints (Hay et al, 1979) The angular impulse is the product of the average joint moment during the propulsion phase and the time of movement To gain insight into the factors affecting jump height achievement, not only do the forces and velocity acting on the whole body before take-off need to be examined, but also examination of individual joints is required

2 2 2 Whole body kinematics

The amplitude of movement of the BCOM is the distance over which the BCOM travels during the concentric phase The greater the movement amplitude of the BCOM, the further the distance over which the body can exert a force and the greater the potential take-off velocity The amplitude the BCOM moves during the concentric phase has been examined in numerous studies (Aragon-Vargas and Gross, 1997a, Bobbert et al, 1986a, Bobbert et al, 1987a, Bobbert et al, 1996, Nagano et al, 1998, Rodacki et al, 2001) These studies have been in close agreement, reporting that the amplitude the BCOM travels of approximately 0 35m However, Nagano et al (1998) and Rodacki et al (2001) found greater amplitudes of 0 49m and 0 48m, respectively Only one of these vertical jumping studies examined how different amplitudes affected the jump height achieved Aragon-Vargas and Gross (1997a) used multiple regression techniques to identify relevant predictors of jump height and found almost all models included this amplitude moves as a predictor of jump height

Vertical jumping is a ballistic movement taking less than a second to perform (Bedi et al, 1987, Bobbert et al, 1987a, Rodacki et al, 2001) A greater amount of time is spent during the vertical deceleration of the body (eccentric phase) than the propulsion (concentric phase) The eccentric phase lasts on average between 0 45s (Bosco and Komi, 1979) and 0 72s (Rodacki et al, 2001), while the concentric phase lasts on average between 0 2s and 0 3s (Bedi et al, 1987, Bobbert et al, 1987a, Jaric et al, 1989) (table 2 6)

Table 2 7 Duration of the eccentric and concentric phases of the CMJ

Study	Number of subjects	Eccentric phase (seconds)	Concentric phase (seconds)	Total (seconds)
Aragon-Vargas and Gross (1997)	52	na	0 32	na
Bedi et al (1987)	32	0 64	0 20	0 84
Bobbert et al (1987a)	10	0 55	0 29	0 84
Bobbert et al (1996)	6	na	0 33	na
Bosco & Komi (1979)	34	0 45	0 22	0 67
Fukashiro & Komi (1987)	1	na	0 26	na
Jaric et al (1989)	39	0 53	0 26	0 79
Rodacki et al (2001)	20	0 71	0 28	0 99

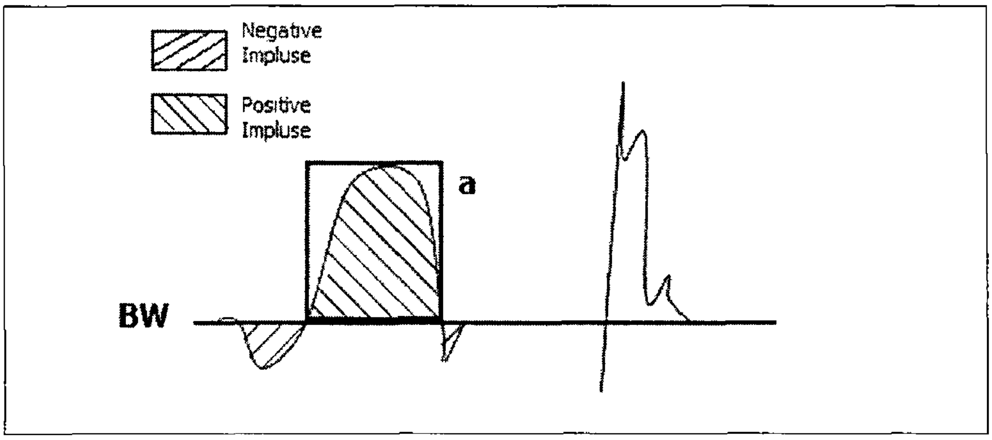
2 2 3 Whole body Kinetics

Through the impulse-momentum relationship vertical impulse, normalised for body weight, is directly related to vertical velocity at take-off Table 2 7 outlines typical magnitudes of the average vertical ground reaction force (vGRF) and vertical impulse reported in the literature Relatively consistent magnitudes of impulse have been reported, ranging between 280Ns and 380Ns (Bedi et al, 1987, Harman et al, 1990, Rodacki et al, 2002) The greater impulse observed by Bobbert et al (1987a) is consistent with the greater jump height and longer concentric phase observed in that study

Table 2 8 Average whole body vGRF and vertical impulse during concentric phase of the CMJ

Study	Number of subjects	Average Force N	Average Force N/kg	Impulse (Ns)
Bedi et al (1987)	32	1836	23 6	369
Bobbert et al (1987a)	10	1715	20 2	497
Bosco & Komi (1979)	34	1017	12 9	na
Harman et al (1990)	18	na	na	281
Rodacki et al (2002)	11	na	na	300

Hay et al (1979) examined vertical impulse over eight separate phases of the CMJ and only found that the vertical impulse during the concentric phase was correlated with jump height Bosco and Komi (1979) however, found net vertical impulse in both the eccentric phase (r = 0 62) and concentric phase (r = 0 78) to be correlated with jump height Findings that positive impulse correlates with jump height adds little to the knowledge of how to enhance jump performance as it is directly related to vertical velocity at take-off (Impulse-momentum relationship) Dowling and Vamos (1993) examined the ratio of negative to positive impulse to gain additional insight and found the ratio to be correlated with jump height (r = -0 514), but impulse in the negative phase alone was not correlated with jump height and the findings may have purely reflected a greater positive impulse rather than a factor of mechanical enhancement The lack of significance for the negative impulse led Dowling and Vamos (1993) to conclude that the countermovement phase is purely to take up the slack in the muscles at the onset of the concentric phase and to allow the muscle enough time to reach maximum activation at the joint angle that allows the greatest moment



Note a) box approximation of total positive force BW body weight

Figure 2 2 Quantitive measures of total force used by Dowling and Vamos (1993)

The force-time curve is a complex function and reveals information such as minimum and maximum values and the rate of force development (RFD), while the area under the curve quantifies the total magnitude of force applied (Figure 2 2) To simplify the force-time relationship many authors have focused on discrete information from the curve or taken a more simplistic approach to quantify the total magnitude of force applied To get an indication of the total force applied Bobbert et al (1987a) and Bosco and Komi (1979) examined the average force during the concentric phase, while Dowling and Vamos (1993) examined the area contained in a box which enclosed the force curve (Figure 2 1) A single point estimate measures have also been used including peak force (Fukashiro and Komi, 1987, Harman et al, 1990, Robertson and Fleming, 1987), and peak force expressed relevant to body weight (Bobbert et al, 1987a) Harman et al (1990) and Robertson and Fleming (1987) report values of peak force approximately 2 3 times body weight (BW) A greater average peak value found by Bobbert et al (1987a) (2 52 BW) is consistent with the greater impulse observed in that study

Table 2 9 Peak vGRF during vertical jumping

Study	Number of subjects	Peak Force (N)	Relative peak force (N/kg)
Fukashiro & Komi (1987)	1	2146	29 0
Harman et al (1990)	18	1697	22 7
Bobbert et al (1987a)	10	2094	24 7

Both peak force (r = 0 519, p< 0 01) and the time from peak to take-off (r = -0 274, p< 0 01) have been found to be significantly correlated with jump height (Dowling and Vamos, 1993) Achievement of peak acceleration of the BCOM or peak force late in the movement may be optimal when high end point velocity is required, but this may require considerably more muscular power and may be limited due to physiological constraints (Dowling & Vamos, 1993) Although Dowling and Vamos (1993) found maximum force to be significantly correlated with jump height, some jumps with a large peak force did not result in a corresponding greater jump height

The rate of isometric force development for the knee joint as measured by greatest change in force has been found to be related to jump performance (r = 0 825) (Paasuke et al, 2001) If a poor correlation between maximum force and the rate of force development exist this would explain why individuals with a high peak force exhibited poor jump performance Rate of force development will be discussed in detail in section 2 2 6 Pandy and Zajac (1991) suggested a rapid increase in vertical force at the start of the concentric phase sustained close to take-off is optimum in vertical jumping

Since vertical jumping requires both high forces and velocity, it is believed that high values of power are desirable (power = force x velocity) Power can be seen as the combination of strength and speed and represents the ability to produce a high level of work through a given distance (Kerin, 2002) (work = force x distance) Bosco and Komi (1979) found average power to be a better predictor of jump height than average vGRF (r = 0 74 and r = 0 51, respectively) Peak whole body power has been found to be the best mechanical predictor of jump height explaining between 52% and 86% of the variance in height achieved (Aragon-Vargas and Gross, 1997a, Dowling and Vamos, 1993, Harman et al, 1990) (r = 0 72, p < 001, r = 0 928, p <0 01 and r = 0 84, p <0 01 respectively) Peak whole body power was also found to be significantly correlated with jump height at an individual level for the ten subjects examined by Aragon-Vargas and Gross (1997b) However, these authors did not find it to be the best predictor of jump height for the three representative individuals examined in detail, instead they found that peak negative impulse, amplitude the BCOM travelled and average power were the best predictor of jump height for the three individuals This study (Aragon-Vargas and Gross, 1997b) is the only study to examine factors that correlate with jump height at an individual subject level, and clearly indicates that individuals differ in which factors are important for success in jump height achievement

Given such a strong association between peak power and jump height, surprisingly peak power has not been evaluated in many jump studies Bosco and Komi (1979) and Harman et al (1990) are in close agreement reporting peak values of 2984W, 3216W (43 W/kg) and 3260W, respectively, while a higher average peak value of 3863W (52 W/kg) was reported by Aragon-Vargas and Gross (1997a) In light of the strong relationship between peak power and jump height, Dowling and Vamos (1993) suggested that simply increasing strength may not be enough to ensure improvement in jump performance, but strength should be increased specifically at high velocities Zajac (1993) examined the influence of muscular strength and speed on vertical squat jump performance using an optimal control model (mathematical based) They found that when strength and speed were enhanced independently by 100%, jump height increased more (120%) from strength enhancement than from speed enhancement (60%)

Table 2 10 Total work done during the concentric phase

Study	Number of subjects	Work done (J)	Relative work done (J/kg)
Hubley and Wells (1983)	6	679	8 5
Fukashiro & Komi (1987)	1	658	8 9
Bosco & Komi (1979)	34	656	8 4

Three studies have examined the total amount of work done in the concentric phase (Bosco and Komi, 1979, Fukashiro and Komi, 1987, Hubley and Wells, 1983) (table 2 10) The greater amount of work done by the subject examined by Fukashiro and Komi (1987) is consistent with the greater jump height observed compared to Bosco and Komi (1979) No comparisons can be made with the study by Hubley and Wells (1983) as no jump performance data is available

While a greater amount of work done can be assumed to increase jump height, provided the distance over which the body moves remains the same, no studies appear to have examined this relationship While Aragon-Vargas and Gross (1997a) did not directly examine the relationship between the amount of work done and jump height, average whole body power and the duration of the concentric phase appeared in tandem within their prediction models for jump height The direct relationship between jump height and work done, both in the eccentric and concentric phase, has yet to be examined

2 2 4 Segmental kinematics

Segmental kinematics and kinetics are the result of how an individual's nervous system uses their neuromuscular capacity to maximise jump height (Aragon-Vargas and Gross, 1997a) The amplitude the BCOM travels, as discussed earlier, is the result of the combined effect of an individual joint's maximum angular displacement, and determines the distance over which work can be done While numerous studies have reported the peak joint angle attained in vertical jumping (table 2 11), none of these have examined the effect changes in peak joint angles have on jump height The greater the peak joint angle the further the distance over which work can be done However, a greater knee angle may not necessarily be optimum Bobbert et al (1996) found a reduced jump height when a lower position of the BCOM at the start of the concentric phase was utilised in a SJ compared to a SJ where the height that was freely chosen in a CMJ was used Factors other than the distance over which to apply force may be important in the selection of the greater angle the knee joint attains in the CMJ Thorstensson et al (1976) determined an optimum knee angle exists for isometric force production, while Bosco et al (1981) found a reduced knee angle enabled better utilisation of the stretch-shorten cycle (SSC) However, due to differences in anthropometrics and neuromuscular capacities between individuals, the optimum joint configurations at the start of the concentric phase may differ between individuals, and analysis at an individual level may be more beneficial

Table 2 11 Peak joint angle during vertical jump

Study	Number of subjects		Radians	Degrees
		Hip	1 12	64 2
Bobbert et al (1996)	6	Knee	1 31	75 1
		Ankle	1 26	72 2
		Hip	1 23	70 5
Bobbert et al(1987a)	10	Knee	1 40	80 2
		Ankle	1 23	70 5
		Hip	1 75	100 0
Jaric et al(1989)	39	Knee	1 71	98 0
		Ankle	na	na
		Hip	1 20	68 6
Rodacki et al (2001)	20	Knee	1 56	89 5
		Ankle	1 64	94 1

Angular velocities of individual joints act in combination to maximize the vertical velocity of the BCOM Table 2 12 outlines peak angular velocity of the joints of the lower extremities during vertical jumping To maximize vertical velocity of the BCOM it appears that these peak joint angular velocities need to be carefully coordinated in both sequence and timing, a factor discussed in 2 3 1

Table 2 12 Peak angular velocity of joints during concentric phase

Study	Number of subjects		Radian/s	Degree/s
		Hip	11 1	636
Bobbert et al (1987a)	10	Knee	16 7	956
		Ankle	16 1	922
		Hip	8 5	487
Rodacki, et al(2001)	20	Knee	12 5	716
		Ankle	10 2	584

2 2 5 Segmental kinetics

The force that the whole body exerts against the ground is the sum of the moments at each joint The net muscle moments about a joint is the sum of moments exerted by agonists, antagonist and passive structures around the joint such as the joint capsule, ligaments and tendons (Bobbert and van Ingen Schenau, 1988) It is of limited use to know that an increase in the total force exerted enhances vertical jump performance

Understandıng how each joınt contrıbutes to thıs total force provıdes more sıgnıficant ınformatıon, as ıt may ıdentıfy areas of defıcıency ın jump performance for an ındıvıdual and guıde future traınıng ınterventıons Investıgatıons ınto the mechanısms of jump heıght achıevement have seldom focused on actıvıty at a segmental level Hay et al (1979) found the average moment for the hıp and knee joınts durıng the first half of the concentrıc phase were sıgnıficantly related to jump heıght (p <0 001), but the magnıtude of the correlatıons were not reported However, no sıgnıficant relatıonshıp was observed for the second half of the concentrıc phase, suggestıng a rapıd development of force early ın the movement ıs desıred

Table 2 13 Peak joınt moments durıng concentrıc phase of CMJ

Study	Number of subjects		Nm	NM/kg
Aragon-Vargas & Gross (1997)	52	Hıp	295 5	4 0
		Knee	220 8	3 0
		Ankle	244 8	3 3
Bobbert et al (1987a)	10	Hıp	403 0	4 8
		Knee	314 0	3 7
		Ankle	263 0	3 1
Fukashıro & Komı (1987)	1	Hıp	313 0	4 2
		Knee	153 0	2 1
		Ankle	125 0	1 7
Ravn et al (1999)	6	Hıp	227 0	3 0
		Knee	438 9	5 8
		Ankle	98 4	1 3
Rodano & Roberto (2002)	9	Hıp	152 8	2 2
		Knee	138 8	2 0
		Ankle	113 0	1 6

An addıtıonal joınt kınetıc parameter that has been examıned ın bıomechanıcal studıes of vertıcal jumpıng ıs peak joınt moment, whıch provıdes a dynamıc measure of the functıonal strength avaılable to an ındıvıdual durıng jumpıng The magnıtude of peak joınt moment ıs approxımately balanced between joınts ın the study by Aragon-Vargas and Gross (1997a) (table 2 12) However, the sıngle subject ın Fukashıro and Komı (1987) had a peak hıp moment nearly 2 5 tımes that of the ankle, whıle Ravn et al (1999) observed an average peak knee moment nearly 4 5 tımes that of the ankle joınt In lıght of the ınter-subject varıabılıty observed ın other studıes (Aragon-Vargas and Gross, 1997a, Rodano and Roberto, 2002), the magnıtudes observed by Fukashıro and Komı (1987) may be partıcular to that ındıvıdual Three of the sıx subjects in the study by Ravn et al (1999) were professional ballet dancers who performed numerous jumps daily with the trunk held vertical for aesthetic reasons, thus increasing the required contribution of knee extensors within these jumps This may have provided a training effect resulting in the ability to achieve a greater knee joint moment

Aragon-Vargas and Gross (1997a) found that peak hip joint moment was the best joint moment predictor of jump height (r = 0 524) and they also included many multiple regression predictor models No knee or ankle moment parameters were evident in any of the regression models reported However, there was an abundance of knee power and isometric knee joint strength parameters within the models In light of the significant correlation that was observed between isometric knee strength and dynamic knee moments during jumping (Aragon-Vargas and Gross, 1997a, Jaric et al, 1989), it is possible that knee moment parameters may have been obscured for statistical reasons However, at an individual level, where strength parameters were not included, peak knee joint moment was significantly correlated with jump height for one of the representative subjects (subject W r = 0 35, p < 0 015) (Aragon-Vargas and Gross, 1997b) Peak joint moment in vertical jumping needs further examination without the interaction of other variables, to determine whether a relationship with jump height exists

The joint moment when angular motion of the joint reverses direction, termed joint reversal (JR) (Aragon-Vargas and Gross, 1997a) was proposed as important in the utilisation of the SSC in vertical jumping (Bosco and Komi, 1979) and influences the total positive impulse during the concentric phase (Bobbert et al, 1996) Aragon-Vargas and Gross (1997a) found hip moment at JR to be significantly correlated with jump height (r = 0 48, p < 0 001) and was evident in several of the best predictor of jump height at a group level Hip moment at JR was also evident in one of the three best regression models for two of the three individuals (Subject A and Subject W) (Aragon-Vargas and Gross, 1997b) However, due to the statistical methodology employed in both studies, it is unknown if a relationship with any other joint moment at JR was present As is evident from the studies outlined in table 2 14, joint moments at joint reversal are similar in magnitude to peak joint moments (table 2 13) If a correlation between joint moment at JR and peak joint moments exists, the inclusion of a peak joint moment within a model including joint moment at JR may not occur

Table 2 14 Joint moments at time of joint reversal in the CMJ

Study	Number of subjects		Nm	Nm/kg
		Hip	280 3	3 77
Aragon-Vargas & Gross (1997)	52	Knee	206 1	2 77
		Ankle	215 3	2 90
		Hip	403 0	4 75
Bobbert et al (1987a)	10	Knee	314 0	3 70
		Ankle	263 0	3 10
		Hip	330 0	4 15
Bobbert et al (1996)	6	Knee	289 0	3 63
		Ankle	220 0	2 76

Table 2 14 outlines four studies that have monitored peak joint power In all the studies reviewed, peak power of the hip joint is lower than that of the knee and ankle In contrast, Gregoire et al (1984) found the power in the knee joint to be less than that of the hip and the ankle, but the magnitude of the differences was not provided

Table 2 15 Peak joint power during concentric phase of the CMJ

Study	Number of subjects		W	W/kg	W/BW
Aragon-Vargas & Gross (1997)		Hip	1204	16 2	1 65
	52	Knee	1487	20 0	2 04
		Ankle	1916	25 8	2 63
Bobbert et al (1987a)		Hip	1524	18 0	1 83
	10	Knee	2549	30 1	3 06
		Ankle	2449	28 9	2 94
Rodacki et al (2001)		Hip			1 28
	20	Knee			1 70
		Ankle			1 87
Rodano & Roberto (2002)		Hip	513	7 3	0 74
	9	Knee	982	13 9	1 41
		Ankle	834	11 8	1 20

As peak whole body power was found to be better correlated with jump height than peak vGRF (Dowling and Vamos, 1993, Harman, 1990), the same may hold true at the segmental level, however, segmental peak power may not be as strongly related to jump height due to ineffective energy transfer between segments (Dowling and Vamos, 1993) Aragon-Vargas and Gross (1997a) found peak hip power to be the best single segmental predictor of jump height (r = 0 67) at a group level and in two of the three individuals examined (subject B r = 0 6, subject W r =0 44) (Aragon-Vargas and Gross, 1997b) The group model was not representative for all individuals Peak hip power was only reported to be a significant predictor for only five of the eight individuals examined (Aragon-Vargas and Gross, 1997b) Peak knee power was also evident in prediction models at a group level, while ankle power was not as relevant (Aragon-Vargas and Gross, 1997a) In contrast, at an individual subject level, ankle power was included regression models for two of the three individuals (subject A and subject B) and was the best single predictor for vertical velocity at take-off for the other individual (subject W) (Aragon-Vargas and Gross, 1997b) However, while the prediction model for the subject B suggested a positive relationship between peak ankle power and jump height, a negative relationship was presented for subject A In light of the problems associated with multiple regression (Section 2 1 4), the relationship between individual joint powers and jump height from these models is unclear Peak hip power and peak hip moment were found to be the best segmental predictors of jump height at both a group and an individual level (Aragon-Vargas and Gross, 1997a, b) Due to the correlation observed between joint isometric kinetics (Jaric et al, 1989) and the effect of inter-joint forces and power flow (Zajac, 1993), possible interaction between joint kinetic parameters may exist This interaction between variables may introduce multicollinearity and would potentially impede the entry of significant parameters into the regression models in the studies by Aragon-Vargas and Gross (1997a, b) For this reason the effect of changes in joint kinetics with respect to jump height needs to be examined in isolation for each variable

Since the sum of work done by all the lower extremities approximates total work done, it would be of interest to know how much work is done at individual joints Table 2 15 outlines three studies detailing the amount of work done at each joint The data provided by Bobbert et al (1986a) for the CMJ was dividend into two groups based on subsequent performance of a DJ, both groups performed the same skill in the CMJ The greatest amount of work done appears to be done at the hip joint This is not surprising given that the greatest muscle mass crosses hip joint In addition to knowledge of the magnitude of work done at each joint, the relative contribution of each joint to total work done may provide additional insight into the movement

Table 2 16 Absolute amount of work performed by the joints during the concentric phase in the CMJ

Study	Number of subjects		J	J/kg
Bobbert et al (1985a)	6 counter group	Hip	234	3 1
		Knee	193	2 6
		Ankle	171	2 3
	7 bounce group	Hip	189	2 5
		Knee	163	2 1
		Ankle	158	2 1
Fukashiro & Komi (1987)	1	Hip	340	4 6
		Knee	116	1 6
		Ankle	102	1 4
Hubley and Wells (1983)	6	Hip	188	2 4
		Knee	330	4 1
		Ankle	161	2 0

Note Counter group utilised amplitude of movement of the BCOM in DJ comparable to the CMJ while a reduced amplitude with a shorter concentric phase was used in the Bounce group

2 2 5 Relative segmental contribution

Knowledge of the relative contribution of a muscle group to the total force or work done is necessary to objectively define which muscle group is dominant at both a group level and for a given individual for a task (Hubley and Wells, 1983) Several techniques have been used to establish the relative contribution of individual joints in vertical jumping Segmental techniques (Luhtanen and Komi, 1979, Miller and East, 1976) are influenced by the mass of the segment, therefore the importance of the trunk may be over estimated Luhtanen and Komi (1978) alternatively examined the contribution of individual joints to total impulse by examining the impulse developed in jumps involving each joint moving in isolation and concluded knee extension contributed 56% Under these highly constrained movements this result is hardly surprising, since of all the conditions, knee extension moved the BCOM through the greatest distance

An alternative approach to examining the contribution of each joint to vertical jumping was employed by Bangerter (1968) This involved altering the strength levels of the extensor muscles about each joint Subjects undertook an eight-week training program focusing on one of the extensor muscle groups, included in the experiment was a control group and one group exercising all leg extensors Of the single muscle exercise groups Bangerter (1968) found that increases in strength of the hip and knee extensors resulted in a greater increase in height jumped, concluding that knee and hip extensors contribute most to vertical jump achievement However, no direct measurement of the mechanism of the enhancement was made

The amount of mechanical work performed at each joint has commonly been used to determine the relative contribution of individual joints (Bobbert et al, 1986a, Fukashiro and Komi, 1987, Hubley and Wells, 1983) (table 2 17)

Table 2 17 Relative contribution of each joint to total work during concentric phase of the CMJ

Study	Number of subjects	Joint	Percentage contribution
Bobbert et al (1986a)	6 counter group	Hip	39
		Knee	32
		Ankle	29
	7 bounce group	Hip	37
		Knee	32
		Ankle	31
Fukashiro & Komi (1987)	1	Hip	51
		Knee	33
		Ankle	16
Hubley and Wells (1983)	6	Hip	27
		Knee	49
		Ankle	23
Nagano et al (1998)	6	Hip	41
		Knee	12
		Ankle	47
Robertson & Fleming (1987)	6 (4 male, 2 female)	Hip	40
		Knee	24
		Ankle	36

Hubley and Wells (1983) showed the relative contribution to work done by each joint during the concentric phase of the CMJ to be approximately 28%, 49% and 23% for the hip, knee and ankle respectively While the knee was the main contributor, the combination of the other two joints cannot be discounted as they made up approximately 51% of total work done However, this pattern did not hold true for every subject, with relative contribution for the knee ranging from 69% to 28% The decrease in the relative contribution of the knee was normally accommodated by an increase at the hip, with the ankle showing least change In contrast, Robertson and

Fleming (1987) found the knee extensors to contribute least toward work done, 24% compared to 40% and 36% for hip and ankle, respectively Given the inter-subject variability in the pattern observed by Hubley and Wells (1983) and the fact Robertson and Fleming only examined 3 subjects (two female, one male), it is possible these subjects were uncharacteristic of the general population In addition, it should be noted that an increase in work done does not necessarily equate with an increase in jump height If a greater ROM is employed, greater work must be done to jump the same height

2 2 6 Rate of force development (RFD)

Not only is the magnitude of force development important in maximising vertical jumping height, the ability to generate force rapidly is purportedly a major component (Kraemer and Newton, 1994) Siff and Verkhoshansky (1998) suggest that for ballistic movements peak force needs to be as high as possible and achieved as quickly as possible Additionally, they contend that in exercises such as jumping, which involve a combination of both eccentric and concentric muscular work, the ability to generate high forces in the transition from eccentric to concentric work is also important To examine the rate of force development (RFD) the slope between two predetermined points of the force-time curve (Dowling and Vamos, 1993, Hakkinen et al, 1991) or the time to reach a certain force has been used (Matavulj et al, 2001, Ugarkovic et al, 2002) Maximal RFD has been examined through analysis of the steepest slope of the force-time curve (Driss et al, 1998, Paasuke et al, 2001, Wilson et al, 1995) Jaric et al (1989) used the exponential coefficient of the force curve While vertical jumping is a dynamic movement, the RFD has typically been quantified by means of isometric strength testing of isolated joints (Jaric et al, 1989, Paasuke et al, 2001, Tomioka et al, 2001) Contrasting findings have been observed for the relationship between the RFD and jump height Jaric et al (1989) found significant correlations between RFD at all three lower extremity joints and jump height (hip $r = 0\ 54$, knee $r = 0\ 46$, ankle $r = 0\ 38$, all $p < 0\ 05$) Paasuke et al (2001) found the peak RFD of the knee joint to be significantly correlated with CMJ height (trained $r = 0\ 83$, untrained $r = 0\ 79$, both $p < 0\ 05$) Marcora and Miller (2000) found the isometric RFD of the knee joint was correlated with CMJ height when a knee angle of 120° was tested (r = 0 69, p <0 05) but not for a knee angle of 90° (r = 0 37, p >0 05) Driss et al (1998) found the time interval from 25% peak force to 50% peak force was correlated with jump height for the left leg (r=-0 63, p <0 01) but was not for the right leg (r=0 15, p>0 05) In contrast, Driss et al (1998) found no relationship between isometric knee extension maximum RFD (steepest slope over 20ms) and jump height (0 20 < r < 0 30, p >0 05) Similarly, Izquierdo et al (1999) found no correlation between maximum RFD and CMJ height for young or middle aged men (0 07 < r < 0 29) The RFD, measured as the time interval between 10% and 90% peak force was not found to be correlated with jump height (Matavulj et al, 2001, Ugarkovic et al, 2002)

However, even if isometric RFD does correlate with jump height, the use of isometric strength testing to determine the RFD of muscle groups to predict performance of a dynamic movement, such as vertical jumping, is problematic Firstly, the question arises over which joint angle should be used to predict performance of a dynamic movement which utilises a relatively large range of joint motion (Kraemer and Newton, 1994) Secondly, power flows between joints in dynamic movements and the efficacy of this power flow has been proposed to be important for success in vertical jumping (Gregoire et al, 1984) Isometric strength testing is a uniarticular action where power flow is negligible Thirdly, jumping is a multiarticular movement which involves leg extensors contracting in a coordinated fashion and requires stabilising action of the trunk and pelvis (Young, 1995) In contrast, with isometric testing other joints are maintained stable throughout testing procedures Finally, the CMJ involves both eccentric and concentric contractions, which differs from the muscular contraction employed in isometric tests, where some authors found correlations with jump height

The importance of RFD in the CMJ itself needs to be examined, only one study appears to have done this Dowling and Vamos (1993) examined the average slope of the force-time curve from the minimum value to peak value but found no significant correlation with jump height (r = 0 027, p > 0 01) However, only one jump was undertaken for each subject, Rodano and Roberto (2002) found that at least twelve samples were needed to find a representative value of jump kinetics Additionally,

Dowling and Vamos (1993) only examined whole body RFD, the RFD at an individual joint may still be important and needs to be examined
Wilson et al (1995) used a modified smith machine positioned over a force platform to measure whole body dynamic RFD during a CMJ They defined RFD as the force developed over 30ms, the impulse over 100ms and the steepest gradient of the force time curve over 5ms The maximum RFD in the CMJ was not found to be correlated with the RFD in an isometric squat test (0 33 < r < 0 36, p >0 05) However, the authors did not examine whether either the dynamic RFD or the isometric RFD correlated with CMJ jump height

A number of other measures of the RFD have been put forward explosive strength, reactive strength and reactive coefficient Siff and Verkhoshansky (1998) defined 'explosive strength' as the ability to produce maximal force in a minimal time and is measured as peak force divided by the time taken to reach it The ability to use the SSC effectively has been termed 'reactive strength' (Young, 1995) or 'reactive ability' (Siff and Verkhoshansky, 1998) The RFD with respect to body weight was termed 'Reactivity Coefficient' (Siff and Verkhoshansky, 1998) The slope of the force up to half the maximum force and the slope from half to peak force was also put forward as a measure of RFD (Siff and Verkhoshansky, 1998) However, no studies appear to have directly investigated the importance of these measures to jump height

2 2 7 Enhancement of jump height due to countermovement

The squat jump is seen as a purely concentric action, however, exercises seldom involve isometric, concentric or eccentric contractions in isolation (Komi, 2000) In many movements body segments are subject to external forces such as gravity acting on the muscles as they lengthen This lengthening phase, where the muscles are acting eccentrically, is often followed by a concentric action of the muscle This forms a natural type of muscle function called the stretch-shortening cycle (SSC) (Komi, 2000, Bosco et al, 1981) The SSC has been shown to enhance performance compared to the concentric contraction alone (Bosco and Komi, 1979, Bosco et al, 1981, Bosco et al, 1982, Cavagna, 1977) In the CMJ the extensor muscles of the lower extremities act eccentrically to actively resist the downward movement during the countermovement

There is ample evidence of jump performance being improved by the use of a countermovement (Asmussen and Bonde-Petersen, 1974, Bobbert et al, 1996, Bosco and Komi, 1979, Bosco et al, 1982b, Fukashiro and Komi, 1987, Harman et al, 1990) Reported increases in jump height achieved in the CMJ over that of the SJ have ranged from 1 7cm (Harman et al, 1990) to 14cm (Fukashiro & Komi, 1987) Comparison between the SJ and the CMJ provides insight into the mechanisms of enhancement due to the countermovement in the CMJ There have been a number of explanations put forward for this enhancement

The freely chosen starting position of the BCOM during SJ is higher than the minimum height of the BCOM attained during the push-off in the CMJ (Bobbert et al, 1996, Harman et al, 1990), reducing the distance over which force can be produced, therefore reducing the distance over which the BCOM can accelerate However, Bobbert et al (1996) found that when a comparable starting position to that of the CMJ was utilised in the SJ the height achieved was still less that of the CMJ Moreover, when a lower position of the BCOM than that of the CMJ was utilised prior to the concentric phase in a SJ, Bobbert et al (1996) found that the jump height was still on average 3 2 cm less than the CMJ

2 2 7 1 Enhancement of mechanical variables

Given that the CMJ will result in greater jump height than the SJ, it follows that a more effective use of the countermovement may result in a greater jump height in the CMJ Many mechanical factors have been shown to be greater in the CMJ than the SJ including peak ground reaction force (Fukashiro and Komi, 1987), force at the start of the concentric phase (Bobbert et al, 1996), average force during the concentric phase (Bosco et al, 1981) and mechanical work done (Asmussen and Bonde-Petersen, 1974, Fukashiro and Komi, 1987, Hubley and Wells, 1983) However, the relationship between varying use of the countermovement and jump height achievement has not been fully examined

The average positive force difference between the CMJ and the SJ has been used as a reflection of the mechanical enhancement due to pre-stretching of the muscles (Bosco et al, 1981, Bosco et al, 1982a) Bosco et al (1981) found that for jumps of similar knee amplitude (mean 71°), the average positive force was 66% greater in the CMJ compared to the SJ Bosco and Komi (1979) found a 40% greater average force with a larger sample (34 PE students) Possible reasons for the lower differences observed by Bosco and Komi (1979) were i) the knee amplitude was not controlled between the SJ and the CMJ, and ii) with the use of power athletes in the study by Bosco et al (1981) in comparison to merely physical education students by Bosco and Komi (1979) , the power athletes may have been able to utilise the countermovement more effectively When examining the effect of knee amplitude on enhancement, Bosco et al (1982a) found the average force enhancement associated with the CMJ over the SJ was 49% and 75% for large (SJ 87 3°, CMJ 89 2°) and small knee (SJ 55 3°, CMJ 51 3°) amplitudes, respectively

There is a greater enhancement of average concentric force in the CMJ over the SJ when a larger force is developed at the end of the eccentric phase (Bosco et al, 1981, Bosco et al, 1982) The enhancement of average force has been found to be greater the larger the instantaneous force at the end of the stretch ($r = 0\ 51$, $p < 0\ 001$) and the faster the pre-stretch of the muscle ($r=0\ 53$, $P<0\ 001$) (Bosco et al, 1981)

Average power has also been found to be higher during the CMJ in comparison to the SJ (Bosco et al, 1981, Bosco and Komi, 1979, Harman et al, 1990) Enhancements of between 81% (Bosco et al, 1981) and 15% (Harman et al, 1990) have been observed in the CMJ over that of the SJ However, as knee angle was not controlled between the SJ and the CMJ these enhancement values may be misleading Harman et al (1990) however, did not find any significant difference in peak force or peak power between the CMJ and the SJ

Since the vGRF is a function of individual joint forces, greater insight may be gained from examination of joint kinetics Two studies compared the joint kinetics of the CMJ and SJ (Hubley and Wells, 1983, Fukashiro and Komi, 1987) Fukashiro and Komi (1987), when testing a single individual subject, found total mechanical work done by the subject during concentric phase of the CMJ was 25% more than the work done during the SJ The amount of work done at the knee and ankle joints was similar between the CMJ and the SJ, and the increase in work was brought about by extra work done at the hip The amount of extra work done at the hip was 116J of the 132J of total extra work done, corresponding to 88% of the total extra work done in the CMJ In contrast, Hubley and Wells (1993) found no significant difference at a group level between the total amount of work done during the concentric phase of the CMJ to that of the SJ, and at the segmental level no clear enhancement pattern was observed when knee flexion amplitude was controlled At an individual level, for one subject the enhancement ratio for the hip and knee joints were 1 23 and 0 79, respectively, while for another subject the opposite pattern was observed with ratios of 0 76 and 1 96 for the hip and knee joints respectively The rank order of magnitude of work done by the joints (hip-knee-ankle) was maintained for the single subject in the study by Fukashiro and Komi (1987) for both the SJ and the CMJ but the pattern was only maintained for 3 of the 6 subjects in the study by Hubley and Wells (1983)

2 2 7 2 Possible mechanisms for enhancement

Enhancement in the performance outcome, and the average concentric force and work done that produces it has been attributed to a number of factors greater force at the start of the concentric phase (Bobbert et al, 1996), storage of elastic energy (Bosco and Komi, 1979, Bosco et al, 1981), contractile component "potentiation" (Cavagna, 1977), spinal reflex of the muscles (Bobbert et al, 1996) and better control of movement (Bobbert et al, 1996) Each of these factors is briefly outlined below

<u>Force at the start of the concentric phase</u>

In general, during maximum muscle contractions it takes time before peak force can be reached This is due to the finite rate of muscle stimulation by the central nervous system, the time constants of the stimulation-active state coupling and the interaction between the contractile elements and series elastic elements (Bobbert et al, 1996) If the active state of the muscle only begins to rise at the start of the concentric contraction, part of the shortening distance is travelled at a sub maximum level, resulting in less work done The muscle may build up a maximum active state by isometric contraction or as a result of an eccentric contraction via a countermovement Therefore, a higher level of force can be achieved in the muscles at the start of the concentric phase in the CMJ in comparison to the SJ (Bobbert et al, 1996) In consequence this facilitates greater work done during the CMJ than the SJ Bobbert et al (1996) found greater moments at the hip, knee and ankle at the start of the concentric phase in jumps involving a countermovement phase in comparison to a SJ, even when the body position at the start of the concentric was the same They concluded the increase in force at the start of the concentric phase provided the majority of the enhancement

However, attributing the enhancement in the total amount of work done in the concentric phase to a greater amount of force at the start of the concentric phase may be misleading Walshe et al (1998), with the use of an isokinetic squatting machine, compared the work output of an isokinetic contraction preceded by three differing forms of muscular contraction, isometric, SSC and rest The SSC condition involved the subject making downward movement similar to that of the CMJ prior to the isokinetic contraction In the isometric condition the force and knee angle was matched to those experienced at the start of the concentric phase in the SSC condition (mean force at start of concentric phase isometric 1169N, SSC 1193N, not significantly different) More work was done in the first 300ms following the pre-stretch in the SSC condition compared to the isometric condition Additionally, a greater amount of power was developed earlier in the movement They concluded that not only the amount of force developed at the start of the concentric phase was important but also the manner in which it was developed Enhancement factors relating to the active pre-stretch of the muscle prior to the concentric phase are outlined below

Storage of elastic energy

The enhancement in jump performance has also been attributed to the release of elastic energy stored in the muscle during the eccentric phase, which is reutilised during the concentric phase (Bosco et al, 1981, 1982, Cavagna et al, 1965, 1968) The eccentric contraction of the muscle causes storage of elastic energy in the series elastic component, mainly the protein titin, the tendons and the cross-bridges (Bosco & Komi, 1979) The myosin filaments are rotated backwards against their natural tendency during the stretch to a position of higher potential energy This in essence causes mechanical work to be stored in the sarcomere cross-bridges that can be reused during the concentric phase, provided the muscles are allowed to shorten immediately after the stretch (Bosco et al, 1982a)

Potentiation

Improvement in performance may also be due to the stretching of active muscle during the eccentric phase, which alters the contractile machinery of the muscle (Bobbert et al, 1996), referred to as "Potentiation" or the "Cavagna effect " (Cavagna, 1977) The exact means by which the contractile machinery is altered does not appear to have been fully explained

Spinal reflex

Active stretching of the muscles during the eccentric phase may trigger spinal reflexes, as well as longer-latency responses, which increase muscle stimulation during the concentric phase (Bobbert et al, 1996) With the increased stimulation the muscles can produce higher forces and thus greater work can be done during the concentric phase

These enhancements are possible provided the muscles are allowed to shorten immediately after the stretch (Bosco et al, 1982a) The lengthened cross-bridges can become detached if the stretch is maintained for too long, or may cause sarcomere "slipping" if the range of stretch is too great (Bosco et al, 1981) Therefore the transition period between the eccentric and concentric phase, called "coupling time" (Bosco et al, 1981) must be kept short A negative correlation ($r = -0\ 35$, $p < 0\ 01$) has been found between the enhancement in average force in the CMJ over that of the SJ (Bosco et al,1981)

Bosco et al (1981) found coupling time to last on average 23 0±14 7ms in the CMJ and increased with greater the movement amplitudes ($r = 0\ 46$, $P<0\ 001$) Bosco et al (1982a) found coupling times of 18 9ms and 44ms corresponding to knee angular displacements of 55 3^{o} and 87 3^{o} respectively Coupling time was reduced with greater force in the eccentric phase ($r = -0\ 47$, $P<0\ 001$), as the increases in stiffness made the transition from the eccentric to the concentric phase take place faster (Bosco et al, 1981)

Variations in the relative amount of muscle fibre type between individuals have been proposed as a possible reason of differences in response to effective utilisation of the SSC between individuals (Bosco et al, 1982a) Fast twitch (FT) and slow twitch (ST) muscle fibers are characterized by different visco-elastic properties resulting in different response to the SSC, depending on the speed of movement (Bosco et al, 1982a) Bosco et al (1982a) found significantly greater force at the start of concentric phase for subjects with more fast twitch fibers in jumps of small amplitude (FT = 30 2±4 8 N kg^{1} and ST 25 9±4 8 N kg^{1}, $p<0\ 05$) but no difference was found for jumps of large amplitude A positive correlation between the %FT and the force at the start of concentric phase for small amplitude jumps was evident ($r = 0\ 57$, $p<0\ 05$), but no relationship was present for large amplitudes Despite the difference in the force at the start of the concentric phase, the relative (percentage) enhancement of force between CMJ and SJ did not differ with fiber type in small amplitude jumps However, there was a greater relative enhancement in jump height with large amplitudes for individuals with a predominance of slow twitch fibres Bosco et al (1982) suggested that since the eccentric phase of small amplitude jumps is short, the greater force at the start of the concentric phase in the FT group is due to faster recruitment of motor units The duration of the eccentric phase, which was relatively long (mean 147ms) was not a limiting factor in jumps of large amplitude, allowing ST fibres enough time to be stimulated The reason for differences in relative enhancement of force between groups was attributed to the attachment-detachment cycle of the sarcomere cross-bridges For small amplitude jumps the coupling time was small (18 9±10 7ms) and was unlikely to be a limiting factor for either fiber types Jumps of larger amplitude are characterized by longer coupling times (44 0±16 8ms) which favours ST fibres as they retain their cross-bridge attachment longer However, a greater number of fibres detach in the FT fibre group, resulting in greater relative utilization of store energy in the ST group

Control of movement

One additional explanation for greater height achieved in the CMJ than the SJ is that the squat jump is a less practiced movement (Bobbert et al, 1996) If a non-optimal control is selected it may affect the movement pattern, resulting in the amount of work done by the muscles being transformed to effective energy being submaximal (Bobbert et al, 1996)

2 3 Coordination

The human movement system is made up of many subsystems including the neural, perceptual and muscular-skeletal systems A motor task is the result of the central nervous system sending impulse volleys to the muscles in light of the expected and actual mechanical demands of the task (Bobbert & van Ingen Schenau, 1988) Coordination has been the focus of both biomechanical and motor control neuroscience studies Biomechanical studies have centred on examining how body segments and muscles interact to perform motor tasks (Hudson, 1986) in order to explain how performance is enhanced or injuries occur (Hamill et al, 1999, Schache et al, 1999)

The previous section (2 2) reviewed studies, which investigated the magnitude of the mechanical output of the lower extremities in vertical jump performance However, mechanical output in maximum effort multi-joint movements is not simply a reflection of the mechanical capacity of the neuromuscular system's ability to produce force but also dependent upon the coordination pattern employed to effectively utilise the work capacity of the muscles (Tomioka et al, 2001, Walshe et al, 1998) Coordination is the process where the multiple and different component parts of a system are brought ınto proper alıgnment ın temporal space and tıme (Turvey, 1990) and refers to the tımıng and sequence of segmental movements Therefore ıt ıs necessary to examıne both the muscle mechanıcal output and the coordınatıon pattern employed to gaın a comprehensıve ınsıght ın to the factors effectıng jump performance

The ımportance of both coordınatıon and mechanıcal capacıty ın vertıcal jumpıng has been hıghlıghted ın three separate studıes, whıch used forward dynamıc control models of vertıcal jumpıng Bobbert and Van Soest (1994) ıncreased peak ısometrıc force ın all lower extremıty muscles resultıng ın an ıncrease ın jump heıght, but only when the pattern of muscle actıvatıon was re-optımısed When the muscle actıvatıon pattern from the orıgınal neuromuscular capacıty was used, the jumpıng movement was dısrupted, resultıng ın a lower jump heıght than that wıth the orıgınal neuromuscular capacıty Nagano and Gerrıtsen (2001) altered peak ısometrıc muscle force, peak muscle shortenıng velocıty and the number of motor unıts recruıted, and re-optımısed the muscle actıvatıon pattern wıth each alteratıon The optımal tımıng pattern of muscle actıvatıon changed wıth each alteratıon of the neuromuscular parameters The change was greatest wıth alteratıons of peak ısometrıc muscle force and not so evıdent for shortenıng velocıty When the optımal muscle actıvatıon pattern from the orıgınal model was applıed to the model wıth altered strength, enhancement of jump heıght was only 14 15cm, compared to 16 62cm when re-optımısatıon had occurred Fınally, Pandy et al (1990) showed wıth the use of an optımal control model that when the actıvatıon of the vastı (knee extensor) was delayed by 10%, vertıcal jump heıght was sıgnıficantly reduced The trunk rotated past the vertıcal and the angular velocıty of the thıgh was reduced, resultıng ın the joınts not beıng fully extended at take-off In lıght of the results of these three studıes ıt ıs possıble that ın addıtıon to examınatıon of mechanıcal output varıables, the varıatıon ın the patterns of coordınatıon may also reveal and explaın dıfferences ın jump performance

2 3 1 Constraınts ınfluencıng movement pattern

For a gıven movement task many constraınts are ımposed on the system Under the dynamıcs systems framework functıonal patterns of coordınatıon emerge under task, information and environmental constraints of the neuro-musculoskeletal system that places a requirement on the system to change it's organizational state (Davids et al, 2000) Constraints are defined as specific requirements of an anatomical, neuronal or biomechanical origin, which impose restrictions on the possible muscle actions of the movement system (Jacobs and van Ingen Schenau, 1992) These constraints provide the limits or conditions for the self-organising processes, reducing the possible movement combinations (Clark et al, 1989) Dealing with these constraints is an important goal in the organisation of muscle actions (Bobbert and van Ingen Schenau, 1988) and should be considered when examining vertical jumping performance Some mechanical constraints that influence the coordination pattern in vertical jumping are outlined below

Intersegmental dynamics

A force generated by a muscle will not only cause acceleration at the joint it spans but also other joints due to the dynamic coupling arising from the multi-articular nature of the body (Zajac et al, 2002) An example of this is in flat foot standing near vertical posture, the soleus can act to accelerate the knee into flexion by accelerating the thigh and shank into extension even though it only spans the ankle This is achieved due to inertia forces being transmitted from one segment to another via joint reaction forces (Zajac, 1993)

Task constraint

During the flight phase, neglecting energy losses due to air resistance, the effective energy of the BCOM remain constant The effective energy refers to the sum of kinetic energy and potential energy (Bobbert and van Ingen Schenau, 1988) The aim of the jump is to maximise the effective energy at take-off, the kinetic energy depends on vertical velocity of the BCOM at take-off, while potential energy is dependent on height of the BCOM above the ground at take-off (Bobbert and van Soest, 2001) The aim is to maximise effective energy as a whole and not one element at the expense of the other

The vertical velocity of the BCOM is most strongly affected by the vertical velocity of the centre of mass (COM) of the upper body, as the upper body has the greatest relative mass During the first part of the jump the increase in vertical velocity of the

COM of the upper body is mainly due to the vertical velocity difference between the upper body COM and the hip joints The difference reaches a peak at about 190ms before toe-off, with relatively constant angular velocity thereafter (Bobbert and van Ingen Schenau, 1988) At this point the hip joint has moved through 20°, which is only part of the shortening range and work capacity of the hip joint If extension of the lower legs was not possible the effective energy of the BCOM would plateau and take-off would occur soon after However, extension of the lower legs is possible and it is at this point that the knee joint begins to extend Extension of the knee joint increases the vertical velocity difference between the hip and the ankle, which exceeds the decline in the velocity difference between the upper body's COM and the hip joints, thus enabling the vertical velocity of the upper body's COM to increase However, in spite of increasing angular velocity of the knee joint, the velocity difference between the upper body's COM and the ankle joint peaks at 60ms before take-off At this instant the knee angle is only approximately at 125° on average, far from maximum extension and only part of the knee's work capacity is used Again the effective energy would plateau if no plantar flexion were possible However, plantar flexion is possible and increases the vertical velocity difference between the ankle and the metatarsal heads, again this exceeds the decrease in vertical velocity difference between the upper body's COM and the ankles, allowing the vertical velocity of the upper body's COM to continue to increase At about 30ms before take-off the vertical velocity difference between the ankle and the metatarsal head reaches a peak (Bobbert and van Ingen Schenau, 1988) It is flexion of the toes that stops ground contact from being lost prematurely but at this stage the magnitude of the vGRF is below body weight so decrease in the vertical velocity is inevitable It is suggested that in order to maximise performance the vertical velocity difference between ends of each segment should peak in a proximal-to-distal sequence (Hudson, 1986) In this way it is hypothesised that uniarticular hip extensors, knee extensors and plantar flexors shorten over their full range and release as much energy as possible to contribute to the body's effective energy at take-off (Bobbert and van Ingen Schenau, 1988)

<u>Anatomical constraint</u>

To prevent injury associated with hyperextension of the joints, the joint's angular velocity has to decelerate to zero at full extension This has been described as an 'anatomical constraint' (Van Ingen Schenau et al, 1987) If uniarticular muscles were only available to decelerate the segments, continued contraction of the extensor muscles towards full extension of the joint would not only be wasteful, but would also be dangerous, as structures that traverse the joint would run the risk of damage (Bobbert and van Ingen Schenau, 1988) Additionally, power would be lost to heat due to excessive eccentric contraction of the flexor muscles (van Ingen Schenau et al, 1987) Biarticular muscles play an important role in not only decelerating a joint, but also transferring energy to a more distal joint to aid in joint extension For example, the biarticular gastrocnemius muscle plays an important role toward the end of the propulsion phase by decelerating knee extension and increasing plantar flexor moments (van Ingen Schenau, 1987)

Geometrical constraint

The aim of the concentric phase is to attain the maximum vertical velocity of the BCOM at take-off The only way to generate linear velocity is to give the segments an angular velocity (Bobbert and van Soest, 2001) The amount the rotation of a segment contributes to the position of the BCOM is dependant on geometric factors Figure 2 3 shows a segment with proximal end *p*, distal end *d* and length *l*

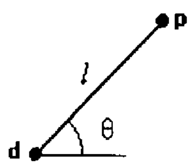


Figure 2 3 Geometrical configurations of typical segment

The vertical difference between *p* and *d* is given by

$$(y_p - y_d) = l \sin\theta$$

where *l* is the distance between *p* and *d*, while θ is the angle the segment's longitudinal axis makes with the horizontal The vertical velocity difference between *p* and *d* is given by

$$(v_p - v_d) = l \cos\omega$$

where ω is the angular velocity of the segment and v is linear velocity

When θ is 90°, the vertical difference between *p* and *d* is *l* (since sin θ = 1) and the velocity difference is zero no matter how high the angular velocity is (since cos ω = 0) As a result the vertical velocity difference between the segment end points may peak and decline in spite of constant or increasing angular velocity Dealing with this phenomenon is an important goal in organising muscle actions (Bobbert and van Ingen Schenau, 1988) In vertical jumping when the knee approaches full extension the velocity difference between the hip and the ankle will approach zero and the transformation of knee angular velocity to translation of the BCOM will be less effective

Vertical jumping is initiated by the acceleration of the trunk through activation of the gluteus maximus Due to geometrical constraints the effect of the angular velocity of the trunk on the rise of the BCOM decreases as it approaches the vertical At this point the angular velocity of the trunk is decelerated by activation of the rectus femoris This allows the gluteus maxims to remain active while also transporting power to the knee via the rectus femoris, thus maintaining the rise of the BCOM If the jump were performed without plantar flexion the body would leave the ground at the instant the vertical velocity difference between the hip and the ankle reached a maximum (Van Ingen Schenau et al, 1987) The larger body segments would pull the smaller segments from the ground when they reached a critical velocity with respect to the ground (Bobbert et al, 1986a) Bobbert et al (1986b) found peak vertical velocity difference between the BCOM and the ankle joint to occur at a mean knee angle of 128° Van Ingen Schenau et al (1987) found the velocity difference between the hip and the ankle to peak at a mean knee angle of 132°, and the mean knee joint angle at the start of the push-off phase to be 82° This corresponds to only 50° of a total possible extension range of 98° (from 82° to 180°), thus a large part of the knee extensor's capacity to shorten and liberate energy could not be used for external work (Bobbert et al, 1986) Due to fast plantar flexion, the hip joint can accelerate up to 25ms before take-off (Van Ingen Schenau et al, 1987), thus enhancing jump height

Moment distribution constraint

During vertical jumping the vGRF must be directed more or less vertically through the midline of the body through the BCOM If forces are directed elsewhere the whole body would rotate and/or energy would be dissipated horizontally This would result in a significant reduction in jump height During the countermovement the body has a tendency to rotate forward which must be counteracted by directing the resultant vGRF vector in front of the BCOM, while in the concentric phase the body has a tendency to rotate backwards which must be counteracted by directing the resultant vGRF vector behind the BCOM (Voigt et al, 1995)

2 3 2 Biarticular muscles

Uniarticular muscles will always act to rotate a joint it spans in the direction of applied muscle moment consistent to its anatomical classification However, biarticular muscles may also act to rotate a joint in the opposite direction than the muscle moment due to muscle moments of other joints inducing a stronger counter angular acceleration of the joint (Zajac et al, 2002) Muscles can redistribute segmental energy by accelerating some segments and decelerating others such that the energy reduction due to deceleration of one equals the energy increase of the other (Putnam, 1991, Zajac et al, 2002) Zajac (1993) suggest that in jumping, uniarticular extensor muscles provide most of the propulsive mechanical energy, uniarticular flexors are virtually non-contributory and biarticular muscles fine-tune the coordination The extent to which energy transfer occurs has been controversially viewed

In vertical jumping energy transfer is able to occur because during plantar flexion, the knee and hip joints have high angular velocity This results in a lower shortening velocity for the biarticular muscles than the mono-articulator muscles This allows the biarticular muscles to deliver more force and consequently allows power generated by the gluteus maximus to extend the knee joint through seemingly opposing actions of the gluteus maximus and the rectus femoris (van Ingen Schenau et al, 1985) Timely activation of the rectus femoris decreases the angular acceleration of the trunk and coupled with the onset of knee extension, transfers power from the hip to the knee A similar mechanism allows power to be transferred from the knee to the ankle via the gastrocnemius (van Ingen Schenau et al, 1985) During the last 20-40ms of the propulsive phase of the jump the extensor forces of the knee and ankle reach peak velocity and are not able to deliver notable force at such velocities It is the biarticular muscles, which deliver power during this period, that exhibit relatively slow contractile velocities due to the opposing effect on muscle length by the motion of the joints crossed (Gregoire et al, 1984)

2 3 3 Coordination in Vertical jump

The optimum coordination of a given task falls somewhere on a continuum from sequential to simultaneous It is proposed that a task where the object is light or where the distal end is open employs a sequential pattern (proximal to distal) (Hudson, 1986) A proximal-to-distal sequential pattern has been found for kicking (Davids et al, 2000), throwing (Button et al, 2003) and the volleyball serve (Temprado et al, 1997) When the object is heavy or the distal end is closed, such as in weight lifting, it is proposed that the optimum pattern is more simultaneous (Hudson, 1986) Tasks where velocity is important the pattern is expected to be more sequential However, when large forces or accuracy is required the pattern is expected to be more simultaneous Both patterns have been hypothesised for maximal vertical jumping (Hudson, 1986)

From vGRF data, Bobbert and van Ingen Schenau (1988) found that the BCOM rises linearly up to about 30ms before take-off During the first part of the push-off phase, the rise in the BCOM is primarily due to the extension of the trunk The relative contribution of the trunk decreases in the course of the push-off as the relative importance of leg extension increases Extension of the legs not only contributes via a rise in the COM of the legs but mainly due to raising the hip joints, thereby increasing the height of the COM of the upper body (Bobbert & van Ingen Schenau, 1988)

A few studies have examined the timing and sequence of electromyographic activity of key lower extremity muscles during vertical jump performance (Bobbert and van Ingen Schenau, 1988, Ravn et al, 1999, van Soest et al, 1985) However, it is at the joint kinematic and kinetic level, where the final movement pathway is observed, is the area where the coordination pattern has been most frequently examined (Bobbert and van Ingen Schenau, 1988, Hudson, 1986, Rodacki et al, 2001) The following section outlines the subsequent coordination pattern that has been observed in the CMJ in light of the various constraints imposed on the system

2 3 3 1 Pattern of joint extension

The initiation of joint extension, also refer to as joint reversal (JR), has been reported to occur for the CMJ in a proximal-to-distal sequence, starting with the hips, then the knees followed by the ankles (Gregoire et al, 1984) This pattern is in close agreement with the findings from dynamic optimisation models (Bobbert and van Soest, 2001) One explanation for the sequential pattern observed is that all extensor muscles are activated simultaneously but the upper body obtains additional vertical acceleration, which exerts a downward force on the lower limb restricting extension or even causing additional flexion Hudson (1986) found additional flexion in the lower limbs in 13 of the 20 subjects tested However, Bobbert and van Soest (2001) disputed this idea suggesting if a simultaneous pattern was desired in the CMJ, surely a muscle activation pattern to achieve it would have been learnt by now

Results of electromyographic analysis also do not support the hypothesis that extensor muscles are activated simultaneously, rather they become maximally activated in the sequence of hip extensors, knee extensors and plantar flexors (Bobbert and van Ingen Schenau, 1988) Bobbert and van Ingen Schenau (1988) found that m gluteus maximus, a hip extensor muscle, was maximally active at the start of the push-off phase, while the knee extensor, m vastus medialis, was only 62% activated and the plantar flexor, m soleus was only 26% activated Approximately 90ms were observed between peak activation of these muscles (m vastus medialis was 190ms before take-off, m soleus was 100ms before take-off)

Table 2 18 Timing of joint reversal to take-off (absolute and relative to total duration)

Study	number of subjects		Hip (s)	Knee (s)	Ankle (s)
Jensen et al (1994)*	6 male	abs	0 28	0 21	0 19
		rel	0 44	0 59	0 62
Rodacki et al (2001)	20 male	abs	0 38	0 28	0 27
		rel	0 62	0 72	0 73
Rodacki et al (2002)	11 male	abs	0 39	0 31	0 27
		rel	0 59	0 66	0 71

Note * = data from Jensen and Phillips (1991) study

A proximal-to-distal sequence of joint extension has been reported for vertical jumping (Jensen and Phillips, 1991, Rodacki et al, 2002) Rodacki et al (2001) found the reversal of the hip joint occurred on average 100±6ms before the knee joint, which occurred on average 7±44ms before the ankle joint However, a proximal-to-distal pattern was not always observed, with the ankle preceding the knee in 3 of the 12 subjects In a subsequent study, Rodacki et al (2002) found delays of 74±13ms and 45±40ms between the hip and knee, and the knee and the ankle respectively While these intervals are longer than reported by Rodacki et al (2001), the interval between the extension of the knee and the ankle was variable and in some cases ankle extension preceeded that of the knee Likewise, Jensen and Phillips (1991) found a proximal-to-distal sequence on average, but this pattern was not always present Clarke et al (1989) reported that the hip joint reversal was always before the knee for the 12 female volleyball players and gymnasts examined Even greater variability was evident in a study of 52 physically active male college students by Aragon-Vargas and Gross (1997) In 23 of the subjects a proximal-to-distal pattern was observed, however, for 21 subjects while the hip was extended first, the ankles were extended before the knee joints The remaining 8 subjects used another pattern including one subject utilising a distal-to-proximal sequence

Aragon-Vargas and Gross (1997a) did not find the sequence of joint reversal to be related to jump height achieved when differences between individuals were examined However, when differences in repetitions of a subject's own movement was examined the sequence of joint reversal was found to be a significant predictor of jump height for three of the eight individuals examined (Aragon-Vargas and Gross, 1997b), including it being the best single segmental predictor of jump height for one individual (subject A $r = 0\ 65$, $p < 0\ 001$) Aragon-Vargas and Gross (1997a) measured the coordination of joint reversal from a purely qualitative perspective and did not measure the extent to which deviations from a given pattern affected jump performance Often when a sequence is reported the time interval between events has been within the ±1 frame measurement error (Jensen and Phillips, 1991, Rodacki et al, 2001) Therefore, many of the results involving close occurrences of events must be viewed with caution

Hudson (1986) when examining the coordination pattern of segments, found jumps typically to be initiated with extension of the trunk (HAT) followed by the thighs then the shank at intervals of 44ms and 39ms, respectively The interval between segment extensions was highly variable with a range of between 170ms and 220ms for the time difference between the trunk and thigh, and the thigh and shank, respectively The absolute timing between the trunk and the thigh and the thigh and shank was about 50ms The pattern was not consistent for all subjects Of the 20 subjects examined, 8 initiated thigh extension prior to the HAT, 2 initiated thigh extension prior to the trunk, while 2 extended the shank before the thigh Bobbert and van Ingen Schenau (1988) also examined the initiation of extension of the segments and found that at a group level the trunk began to extend 330ms before toe-off followed by the thigh (270ms), the shank (200ms) and the foot (150ms) The time delays between the trunk and thigh (60ms) and between the thigh and the shank (70ms) were greater than those reported by Hudson (1986)

2 3 3 2 Timing of peak angular velocity

Maximizing velocity of joint rotations may be important from a mechanical perspective (Bobbert and van Ingen Schenau, 1988), likewise as with timing of joint reversal, correct timing of peak angular velocity may be necessary Hudson (1986) found the angular velocity of the trunk was first to peak followed by the thigh and then the shank, at intervals of approximately 29ms and 6ms, respectively Variability was evident at the hip, but a consist coordination pattern was observed at the knee with a range of only 30ms between the thigh and the shank Again this sequential pattern was not observed in all of the 20 subjects, with 11 subjects reaching peak velocity of the thigh before the trunk and one reaching peak velocity of the shank before the thigh Bobbert and Van Ingen Schenau (1988) found angular velocity of the trunk to peak at 190ms on average before take-off, with the rest of the segments peaking 30ms before take-off

Table 2 19 Mean timing of peak joint velocities (absolute and relative to total duration)

Study	number of subjects		Hip (s)	Knee (s)	Ankle (s)
Jensen et al (1994)	6 male	abs	0 040	0 037	0 030
		rel			
Rodacki et al (2001)	20 male	abs	0 080	0 068	0 080
		rel	0 92	0 93	0 920
Rodacki et al (2002)	11 male	abs	0 074	0 066	0 067
		rel	0 928	0 929	0 928

Table 2 19 shows the timing of peak angular velocity of each joint for three studies Timing of peak joints velocities appear to occur in close proximity Jensen and Phillips (1991) found that for 5 of the 6 subjects they tested, all joint angular velocities peaked within 12ms of each other Clarke et al (1989) also reported the delay in peak angular velocity between the knee and ankle was on average within the measurement error

Since segments are different lengths, rotation of each segment will contribute differentially to the rise in the BCOM For this reason Bobbert and Van Ingen Schenau (1988) examined the vertical velocity difference between the proximal and distal ends of each segment A proximal-to-distal sequence was found for the peak vertical velocity difference between proximal and distal ends of each segment Bobbert & Van Ingen Schenau (1988) suggested that as the purpose of segmental rotations during the concentric phase of the jump was to increase the vertical height of the BCOM, the vertical difference between proximal and distal ends may peak and decline in spite of constant angular velocity of the segment due to geometric factors, dealing with this may be an important goal in the organisation of muscle actions A proximal-to-distal pattern was observed in the peak velocity difference, with the trunk segment peaking at 190ms before take-off followed by the thigh, shank and foot at intervals of 80ms, 70ms and 10ms, respectively (Bobbert and Van Ingen Schenau, 1988) Aragon-Vargas and Gross (1997) also reported a proximal-to-distal sequence in peak vertical velocity difference between the proximal and the distal ends of a segment in 42 of the 52 subjects examined, however, no values of delay were given

2 3 3 3 Tımıng of peak joınt power

The temporal delay between peak joınt power and take-off ın the CMJ for three studıes are outlıned ın table 2 20

Table 2 20 Mean tımıng of peak joınt power prıor to take-off (absolute and relatıve to total duratıon)

Study	number of subjects		Hıp (s)	Knee (s)	Ankle (s)
Rodackı et al (2001)	20 male	abs	0 300	0 113	0 090
		rel	0 700	0 890	0 910
Rodackı et al (2002)	11 male	abs	0 204	0 116	0 070
		rel	0 780	0 880	0 930
Bobbert et al (1986c)	10 male	abs	na	na	0 050
Bobbert and van Ingen Schenau (1988)	10 male	abs	0 170	0 600	0 050

Rodackı et al (2001, 2002) found a proxımal-to-dıstal pattern ın peak joınt power ın the CMJ, wıth delays of approxımately 100ms observed between joınts Low varıabılıty was observed at the ankle and knee suggestıng a robust pattern Bobbert and Van Ingen Schenau (1988) also found a proxımal-to-dıstal sequence of joınt power to occur for 10 male volleyball players studıed The temporal sequence ın peak joınt power occur first wıth the hıp at approxımately 170ms before toe-off followed by a delay of 110ms for the knee joınt (60ms before take-off) and the ankle shortly after at 50ms before toe-off However, the delay between the knee and the ankle was wıthın ±1 frame measurement error No measure of varıabılıty ın tımıng was gıven, nor was ıt stated ıf thıs pattern was observed ın all subjects Gregoıre et al (1984) found peak power ın the hıps to occur before that of the ankles, however, the extent of the delay was not stated They reported that the power of the knee joınt showed a dramatıc drop ın the last part of the jump, at the same ınstant the ankle joınt peaked

2 3 4 Coordination as a predictor of jump height

Aragon-Vargas & Gross (1997a) found that the time difference between joint reversal was not a significant predictor of jump height between individuals This is in contrast to the findings of Hudson (1986) who suggested very small delays between adjacent segments are desired, however, no correlation was give with jump performance However, Aragon-Vargas & Gross (1997) examined only the timing between the first and last joint reversals, while Hudson (1986) examined adjacent segments When examining individual subjects Aragon-Vargas and Gross (1997b) did however find the sequence of joint reversal was the best single predictor of jump height accounting for 42% of the variation for one of the individuals and was included in a predictor model for another individual This was purely a qualitative measure and the extent to which the pattern varied from a proximal-to-distal sequence was not examined There was a negative relationship between the occurrence of a proximal-to-distal sequence and jump height, which is in disagreement with other studies where a proximal-to-distal sequence was assumed optimal (Bobbert & van Ingen Schenau, 1988, Hudson, 1986)

Tomioka et al (2001) calculated the quadratic term of the average relative phase angle based on the expectation that the relationship was non-linear Both the quadratic (r=0 71, p=0 01) and linear terms (r=-0 64, p=0 03) were correlated with maximum jump height during the concentric phase, but no relationship was found for the counter movement phase There was no significant relationship between isokinetic knee strength and coordination (r=0 32, p=0 31), both contributed independently to vertical jump height This is in disagreement with finding of Bobbert and Van Soest (1994) and Nagano and Gerritsen (2001) who with the use of dynamic optimisation models found that that changes in strength need to be accompanied by changes in coordination pattern to utilise the increased strength In light of the importance of optimal coordination for a given neuromuscular capacity, the effect of changes in the timing of key events of adjacent joints should be examined in relation to jump height achievement

2 4 Training interventions to increase jump height

In vertical jumping, as in any sporting task, it is the properties of the neuromusculoskeletal system and the control of the movement that ultimately determine the potential performance outcome, which in the case of vertical jumping is the height achieved (Bobbert and van Soest, 1994) Control of the movement refers to the technique, timing and coordination of the movement (Bobbert and van Soest, 1994) and can be improved with guided repetition of the movement (Bobbert, 1990) The properties of the neuromusculoskeletal system include anatomical characteristics (e g mass distributions, limb length and muscle moment arms), biochemical characteristics (e g , enzyme activities and substrate concentrations in the muscles), physiological characteristics (e g muscle strength, muscle fibre composition) (Bobbert and Van Soest, 1994) and neural characteristics (e g motor unit recruitment, firing rate) Anatomical characteristics are more or less given but training may enhance many of the biochemical, physiological and neural characteristics
Many components of the neuromuscular system have been proposed to influence jump height achievement, both relating to the concentric phase alone and the SSC as a single neuromuscular action The height an athlete achieves is determined primarily by the vertical velocity of the BCOM at take-off Through the impulse-momentum relationship, it is clear a large amount of force is required In vertical jumping the athlete has a limited time to apply force before leaving the ground, therefore a large amount of force must be applied as quickly as possible For this reason athletes seek to maximise power Since power is the product of the amount of force and the velocity of the movement, it is often reasoned that increasing the maximum amount of force applied is all that is required of a strength training program (Plisk, 2001) There is a clear relationship between the cross-sectional area of the muscle and the greatest amount of force that can be produced (Fry and Newton, 2002) Once the athlete has achieved the upper limit for specific muscle tension for a given cross-sectional area (40-45Ncm ^{1}) hypertrophy is required (Plisk, 2001) The most common form of training to achieve hypertrophy is heavy resistance training involving repetition of a load 60-80% of one repetition maximum (1RM) (Hakkinen, 2002) Wiscøff et al (2004) found 1RM half squat to be significantly correlated with jump height ($r=0\ 78$, $p<0\ 02$) Additionally, isometric strength has been found to be signifiacntly correlated with vertical jump height (Driss et al, 1998, Eisenman, 1978, Hakkinen,

1991, Jaric et al, 1989) In direct contrast however, a number of studies have found no significant relationship between isometric strength and jump height (Marcora and Millar, 2000, Paasuke et al, 2001, Young et al, 1999a), suggesting other elements of the neuromuscular system are more important in vertical jump performance

Since the time available to apply force in vertical jumping is limited, high amounts of force need to be applied as early in the movement as possible Therefore, training is often aimed at improving the RFD and to move the force-time curve up and to the left resulting in a greater impulse during the limited duration (Plisk, 2001) In a movement of high velocity the ability to produce force at higher velocities is paramount Hakkinen (1991) stated that for explosive movements the principle of specificity of training must be followed, utilising light loads which may be moved quicker, the muscles are highly activated and contract at high velocity Both isokinetic strength at velocities in excess of $360^{o} s^{-1}$ (Saliba and Hrysomallis, 2001) and RFD (Jaric et al, 1989, Marcora and Millar, 2000, Paasuke et al, 2001) have been found to be significantly correlated with jump performance

The use of a countermovement prior to the concentric phase has been shown to enhance vertical jump height (section 2 2 7) Pre-stretching the muscle has been proposed to increase the amount of energy stored in the muscle (Ausmussen and Bonde-Petersen, 1974, Bosco and Komi, 1979) and increases the neural stimulation of the muscle via the stretch reflex (Bosco et al, 1982, Cavagna, 1977) The extent to which these factors enhance jump height are dependant on elements of the neuromuscular capacity, such as the capacity to control and utilise high eccentric loads, coupling time between the eccentric and concentric phase and the ability to store and utilise elastic energy

The essence of strength resistance training is to enable the muscles to release more energy Assuming the distance over which the muscles shorten and the duration of the concentric phase remain the same or reduce, the only way the muscles can release more energy is if they increase the ability to produce a greater power output (Bobbert, 1990) In order to increase the power output capacity of the muscles an overload must be induced This implies that exercises chosen must result in the muscles producing a higher mechanical output (higher forces and power) than during the CMJ

Adaptations to the neuromuscular system and resulting improvements in the performance are specific to the form of training employed Due to the specificity of the adaptations of the neuromuscular system the training intervention employed must be a close match to the CMJ This match includes the muscle groups used, the movement pattern employed, the ROM the joints are brought through, the velocity of contraction and the type of muscle action employed (Fry and Newton, 2002) Additionally, the emphases placed at different points of the movement may need to be similar to the CMJ For example the joint angles where peak moment occurs may need to be similar between the chosen exercise and the CMJ

2 4 1 Training methods to improve neuromuscular capacity

Several forms of neuromuscular training have been employed to enhance CMJ performance via the enhancement of some if not all of the above components These include heavy resistance training (Blattner and Noble, 1979, Toumi et al, 2001), power training (Plisk, 2001), ballistic training (Hunter and Marshall, 2002, Hakkinen et al, 1985) and plyometric training (Blattner and Noble, 1979, Brown et al, 1986, Matavulj et al, 2001) or a combination of the above (Clutch et al, 1983, Hunter and Marshall, 2002)

Heavy resistance training involves moving a heavy load (close to the athletes single repetition maximum (1 RM)) through a given range at relatively slow velocities Due to the velocity specificity of training effect, heavy resistance training may mainly be beneficial at the start of the concentric phase where the movement is slower, with a lesser effect at higher velocities (Newton, 1998) For activities such as vertical jumping where the time available to apply force is limited, the muscles must exert as much force a possible in a short period of time Therefore, a high rate of force development (RFD) is desired While heavy resistance strength training may enhance maximum force it may come at the expense of a decrease in rate of force development (fig 2 4) (Kraemer and Newton, 1994, Kerin, 2002)

In contrast to heavy resistance training, power training or "explosive" resistance training involves moving a lighter load but at higher velocities (Fry and Newton,

2002) This has been proposed to result in improvements in both RFD and peak force, shifting the force-time curve up and to the left However, changes at the high force portion are smaller than those resulting from heavy resistance training but may enable faster development of forces in the early portion of the movement These specific changes may be due to explosive resistance training causing an increase in the amount of neural input This increase is due to rapid voluntary and/or reflex induced enhancement during a short period of time This is evident in the shift in EMG-time curves (Fry and Newton, 2002)

In both heavy resistance and explosive power training, the load is decelerated towards the end of the range of joint extension In the traditional bench press the bar is decelerating for 24% of the concentric phase for maximum loads and 52% for lighter loads (Newton, 1998) The problem of deceleration can be overcome if the athlete throws the weight or jumps at the end of the extension phase This has been termed “ballistic” resistance training (Newton, 1998) Ballistic training for jumping may take the form of a movement from a squatting position rapidly lifting a weight so as the feet leave the ground as the body becomes upright or jumping with a weighted vest (Hunter and Marshall, 2002) Ballistic training may present problems of high forces upon landing or when catching the falling weight

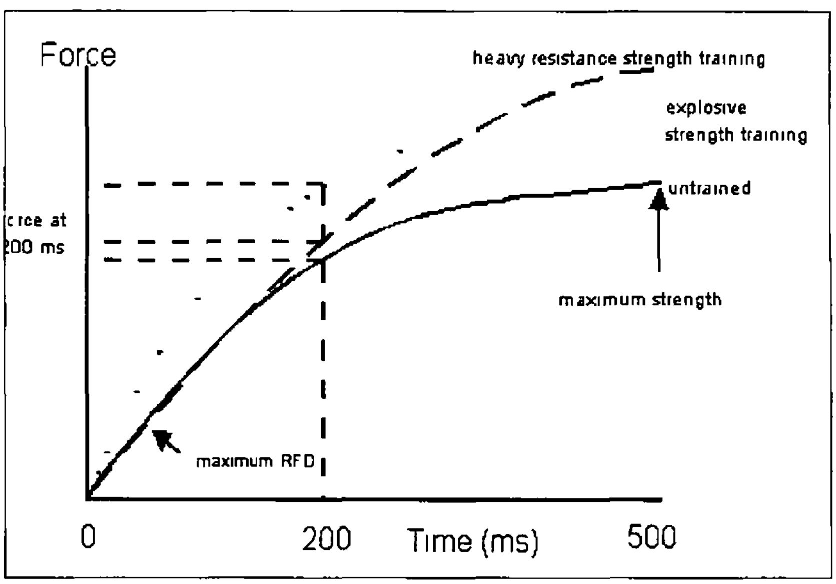


Figure 2 4 Isometric force-time curve indicating maximal strength, maximal RFD following three types of training program (Newton R U from www innervations com)

Another aspect of strength for jumpers may be elastic or reactive strength (Moura and Moura, 2001) Reactive strength can be defined as the ability to utilise the stretching of the muscle during the eccentric phase and the ability to change from an eccentric to a concentric contraction (Young, 1995) Vertical jump performance has been shown to respond to training which involves performing a SSC movement with a greater eccentric load and a more rapid stretch than which they are accustomed to (Kerin, 2002) These activities, termed plyometrics are thought to develop the capability for enhancement of muscular power production and strengthen the neuromuscular system due to the virtue of greater forces imposed upon the system (Lees and Fahmi, 1994) One of the most popular plyometric drills is drop jumping (DJ), which involves falling from a raised platform and upon landing immediately performing a vertical jump (Bobbert, 1990) The dynamic characteristics and coordination of drop jumping are thought to provide qualitative specificity to the CMJ (Bobbert, 1990, Kiren, 2002, Young et al, 1999) Additionally, drop jump training purportedly enhances the ability to utilise the SSC and increases the overall neural stimulation The delay between the eccentric and concentric contractions is due to a electromechanical delay in the muscles and is referred to as the "amortization" (Toumi et al, 2001) or "coupling" phase (Bosco et al, 1981) Drop jumping has been proposed to train the neuromuscular system to make a rapid transition from eccentric to concentric contractions, reducing the coupling time and allows greater utilisation of the SSC (Kerin, 2002)

2 4 2 Changes in kinetic parameters in drop jumps

The enhancement in jump height following a training program that includes drop jumps has been suggested to be due to an improvement in the mechanical output of the muscles, triggered by an overload of the muscles during drop jumping (Bobbert et al, 1987b) A number of studies have reported greater jump height in the DJ compared to the CMJ (Asmussen and Bonde-Petersen, 1974, Lees and Fahmi, 1995) but few studies have examined the difference in the kinetics that may have caused the increase in height achieved (Bobbert et al, 1986a, Bobbert et al, 1987a, Lees and Fahmi, 1994, Voigt et al, 1995)

2 4 2 1 Drop jump technique

The magnitude of the enhancement in the jump kinetics in the DJ over the CMJ has been found to be influenced by the drop jump technique employed (Bobbert et al, 1986a) Bobbert et al (1986a) asked subjects to perform drop jumps and observed that some subjects chose a jumping strategy that employed a movement amplitude of the BCOM comparable to that utilised during the CMJ The duration of the concentric phase lasted longer than 260ms (mean CMJ 280ms), referred to as a counter drop jump (CDJ) Others individuals preferred a movement with a small amplitude and a positive phase lasting less than 200ms, referred to as the bounce drop jump (BDJ) The choice of the DJ technique seemed arbitrary and was not related to anthropometrical variables The magnitude of kinematics and kinetics reported by Bobbert et al (1986a) and (Bobbert et al, 1987a) where individuals were directed to perform a CMJ and both the CDJ and the BDJ are outlined at a whole body level in table 2 21 and at a segmental level in table 2 22 and table 2 23

Table 2 21 Comparison of whole body concentric phase parameters between CMJ and DJ for the two groups in the study by Bobbert et al (1986a) study and the three conditions in Bobbert et al (1987a)

	Bobbert et al (1986a)				Bobbert et al (1987a)		
	counter group		bounce group				
	CMJ	DJ	CMJ	DJ	CMJ	CDJ	BDJ
Movement amplitude (m)	0 35	0 33	0 33	0 21*	0 37	0 25*	0 13 *o
Phase duration (s)	0 28	0 28	0 28	0 17*	0 29	0 21*	0 13 *o
vGRF at start of phase (N)	1792	1941	1613	3052*	2012	2612*	4015*o
Mean phase vGRF (N)	1555	1562	1531	2082*	1715	1918*	2561*o

Note * value differs from the CMJ
o value differs from CDJ

Table 2 22 Kinematic and kinetic output of CMJ and DJ (Bobbert et al, 1986a)

		Counter group		Bounce group	
		CMJ	DJ	CMJ	DJ
	Hip	1 21	1 38	1 44	2 06*
Angle at JR	Knee	1 34	13 2	1 48	1 76*
(rad)	Ankle	1 34	1 39 *	1 3	1 32
	Hip	343	351	269	270
Moment at JR	Knee	247	308	229	407 *
(Nm)	Ankle	236	249	193	420 *
	Hip	366	368	344	305
Peak Moment	Knee	279	331	276	414 *
(Nm)	Ankle	266	279	246	440 *
	Hip	1551	1338	1405	1203
Peak Power	Knee	1657	1762	1481	1936*
(W)	Ankle	1886	1776	1829	2425
	Hip	234	187 *	189	84 *
Work	Knee	193	215	163	146
(J)	Ankle	171	157	158	203 *

Note * value differs from the CMJ

For the individuals that utilised the CDJ technique, the amplitude of movement and duration of concentric phase did not differ to that of the CMJ resulting in similar kinematics, with the exception of less dorsi-flexion and a reduced but not statistically significant hip flexion This resulted in less hip work done, the only kinetic difference observed In contrast, the BDJ was characterised by reduced amplitude of movement and a shorter duration of the concentric phase This resulted in a greater vGRF at the start of the concentric phase and higher mean force but less work done due to the reduced amplitude of movement The reduction in the amplitude is attributed to a reduction in knee and hip flexion As less time was available to decelerate the BCOM greater vGRF were evident at the start of the concentric phase, which were manifested in greater knee and ankle joint moments at joint reversal Both average moment and peak moment at the knee and ankle joints were greater than during the CMJ The knee joint was the only joint that exhibited an increase in peak joint power during the BDJ compared to the CMJ, while a large but non-significant increase was evident at the ankle joint Peak hip joint power was also reduced

In light of DJ technique altering the kinetics of the jump, Bobbert et al (1987a) conducted a more controlled study where subjects were asked to perform a series of jumps from 20cm utilising both the CDJ and the BDJ, which were compared to the CMJ Kinematic and kinetic variables reported by Bobbert et al (1987a) are outlined in tables 2 21 for whole body parameters and table 2 23 for segmental parameters Three points that must be noted when comparisons are made with the previous study relating to technique Firstly, drop height was reduced by 20cm (see section 2 2 7 for more detailed discussion on changes with drop height) Secondly, given that trained volleyball players were used as opposed to handball players, training specificity may have lead to different responses to drop jumping The skill level appears to be greater in the volleyball group, evident by a 5cm greater CMJ height on average Finally, a shorter duration of the concentric phase and amplitude of movement of the BCOM was utilised in both forms of drop jumping compared to the CDJ in the study by Bobbert et al (1986a) The mean duration of the CDJ (210±30ms) approached the criteria for the BDJ (<200ms) set out in the previous study It appears both forms of drop jumping exhibit characteristics of the BDJ in the previous study, which must be taken into account when examining the response to the drop jumping stimulus on the kinetic parameters The CDJ in the study by Bobbert et al (1986a) did not differ from the CMJ with respect to the amplitude of movement of the BCOM or duration of the concentric phase, whereas the CDJ in the study by Bobbert et al (1987a) did and for this reason should be viewed as larger amplitude BDJ

Table 2 23 Mean kinematic and kinetic variables from CMJ and DJ (20cm) (from Bobbert et al, 1987a)

		CMJ	CDJ	BDJ
Angle at JR (rad)	Hip	1 23	1 74 *	2 29 *o
	Knee	1 40	1 51 *	1 93 *o
	Ankle	1 23	1 25	1 26
Moment at JR (Nm)	Hip	403	326	287 *
	Knee	314	473 *	546 *o
	Ankle	263	349 *	586 *o
Peak Moment (Nm)	Hip	422	367 *	310 *o
	Knee	366	488 *	558 *o
	Ankle	310	361 *	602 *o
Peak Power (W)	Hip	1524	1255	1165
	Knee	2549	2796	3004 *o
	Ankle	2449	2482	4529 *o

Note * value differs from the CMJ
o value differs from CDJ

In Bobbert et al (1987a) for both forms of DJ the amplitude of movement of the BCOM, the duration of both the eccentric and concentric phases and the maximum joint angle attained by the hip and the knee were less than during those of the CMJ, and the changes were greater in the BDJ Increases in knee and ankle joint moments at joint reversal and peak values were evident in both forms of drop jumps, consistent with the results for the BDJ found by Bobbert et al (1986a) Additionally, a lower peak hip joint moment was present in both forms of drop jumps and a reduced hip joint moment at joint reversal was evident in the BDJ, but the change experienced in the CDJ was not statistically significant ($p>0\ 05$) In contrast, peak joint power was not significantly different to that of the CMJ for the CDJ but was significantly greater for the knee and ankle joints in the BDJ

While Bobbert and his colleagues identified two distinct techniques, when individuals are asked to perform an unrestricted DJ for maximum jump height, they chose a technique on a continuum from a jump with a small amplitude and short ground contact time to a jump at the other end of the spectrum (Hunter and Marshall, 2002) It has been shown that variance in the duration of the concentric phase of the CMJ also exists (Jaric et al, 1989, van Soest et al, 1985) The use of absolute cut-off durations for the categorisation of jump strategy seems inappropriate Categorisation based on the change in a jump parameter between jump conditions, such as amplitude of movement or duration of a phase may provide a more robust mechanism As a DJ is an example of a SSC movement, categorisation based on the duration of the eccentric phase may prove more appropriate as it may provide a better representation of the characteristics of the stretch applied, while the amplitude of movement provides another means

2 4 2 2 Drop jump height

The enhancement in mechanical output over that of the CMJ in jumps similar to the BDJ, outlined by Bobbert et al (1986a) is due to factors relating to the SSC, which increase with the velocity of the stretch of the active muscles in the eccentric phase and decrease with the coupling phase duration The velocity of stretch the muscle experiences is dependent on the peak negative velocity of the BCOM, which may be varied by increasing the drop height preceding the jump (Bobbert et al, 1987b)

Asmussen and Bonde-Petersen (1974) compared the effect of dropping from three different heights (0 233m, 0 404m and 0 69m) to a CMJ and examined the effect on the jump height achieved and positive phase energy produced They found jump height increased from that attained in the CMJ following a drop from 0 233m and increased further following a drop from 0 404m However, following a drop from 0 69m the jump height did not statistically differ from the height attained in the CMJ At an individual subject level, drop jumping did not result in a greater jump height than that of the CMJ for two individuals, while six individuals continued to increase jump height up to a drop from 0 69m Lees and Fahmi (1995) also found a greater jump height for the DJ than the CMJ when they examined drop heights of 0 12m, 0 24m, 0 36m, 0 46m, 0 58m, and 0 68m, but not for all drop heights The greatest height achieved was from the lowest drop height of 0 12m and jump height diminished as the drop height increased Heights above 0 46m resulted in lower jump heights being achieved than in the CMJ Voigt et al (1995) found no difference in jump height following a drop from 0 3m compared to the CMJ, and a decrease when drop height increased to 0 6m and again to 0 9m In contrast to these findings, many studies have found no difference in jump height following a drop from various heights (Bedi et al, 1987, Bobbert et al, 1987b) Bedi et al (1987) found no difference in jump height achieved following drops of between 0 25m and 0 85m at 0 1m increments, while Bobbert et al (1987b) found no difference in jump height between drops of 0 2m, 0 4m and 0 6m For both studies no comparison was made with a CMJ

Selection of an optimum drop height has traditionally been based on which drop height allowed the greatest jump height achieved (Asmussen and Bonde-Petersen, 1974, Bedi et al, 1987, Young et al, 1999b) In light of the findings by Bobbert et al (1986a) that a drop jump technique utilising a large amplitude of movement may benefit jump height and another technique with a reduced amplitude may benefit the overload of mechanical output of the muscles, selection of drop height based on jump height achieved may not be the best option Young et al (1999b) examined drop heights of 0 3m, 0 45m, 0 6m and 0 75m and found that jump height achieved was greatest at 0 6m but resulted in the second longest contact time However, the lowest drop height (0 3m) resulted in the best reactive strength (jump height divided by contact time) It has been suggested that the larger the reactive strength load the greater the mechanical overload on the muscles (Young et al, 1999b), however, no measurement of joint kinetics were recorded to support this view Few studies have reported changes in kinetics following drops from different heights (Bobbert et al, 1987b, Lees and Fahmi, 1994, Voigt et al, 1995) Lees and Fahmi (1994) found that the lowest drop height examined (0 12m) resulted in the greatest combined enhancement based on the height achieved, the peak vGRF, the peak vertical velocity of the BCOM and the peak whole body power Average mechanical power was found to be enhanced during DJ in comparison to CMJ (Voigt et al, 1995) following a drop of 0 3m and 0 6m, which were both greater than the average mechanical power in jumps from 0 9m Optimal drop height is likely to be dependant on the current neuromuscular capacity and past experiences of an individual From an evolutionary sense the human body may be better tuned neuromuscularly to impacts originating from lower heights, akin to running, hopping and skipping (Lees and Fahmi, 1994) There is no a priori reason why the neuromuscular system would respond more favourably to greater rather than lesser drop heights Lees and Fahmi (1994) concluded that if an optimum drop height exists as a natural biomechanical feature of human neuromuscular system, it is more likely to be lower rather than higher

The kinematics of the jump has been found to differ between drop heights (Bobbert et al, 1987a, Lees and Fahmi, 1994) Bobbert et al (1987b) found no statistical difference in the duration of the eccentric phase between drop heights but the duration of the concentric phase took longer following a drop of 0 6m than it did following 0 4m Much of this could be attributed to a reduced amplitude of movement of the BCOM following a drop of 0 4m (0 03m, p <0 05), brought about by a reduced ROM of the knee joint (0 11rad, p <0 05) Reduced amplitude of movement of the BCOM (0 04m) was also observed by Lees and Fahmi (1994) but only at the lowest drop height of 0 12m, and increased thereafter possibly to absorb the increase in vGRF upon landing from the greater drop heights This was achieved by increasing the ROM of the knee and hip joints

At whole body kinetic level Bobbert et al (1987b) found no difference in the vGRF at the start of the concentric phase between drop heights However, peak vGRF was statistically greater following a drop of 0 4m than 0 2m, and greater again following a drop of 0 6m However, these values appear to be the first impact peak observed and would be unlikely to be related to jump performance The net impulse during the eccentric phase was found to increase with drop height (DJ20 1 97 N s kg^{1} < DJ40 2 47 N s kg^{1} < DJ60 3 09 N s kg^{1}, p < 0 05) but no statistical difference was observed during the concentric phase

When examining the joint moment at reversal, peak joint moment and peak joint power, Bobbert et al (1987b) only found peak ankle joint moment and peak ankle joint power to be statistically different between drop heights Peak ankle joint moment was on average 56N greater following a drop of 0 4m compared to 0 6m and peak ankle joint power was on average 184W greater following a drop of 0 4m compared to 0 6m However, while not statistically significant both peak ankle joint moment and power following a drop of 0 4m was greater than that developed following a drop of 0 2m At both the knee and hip joints no statistically significant differences were observed between drop heights However, the mean knee joint moment at joint reversal, peak knee joint moment and knee joint power were greater following a drop of 0 4m but not statistically different compared 0 2m and 0 6m possibly be due to greater variability observed at the knee joint Likewise a greater but not statistically significant ankle joint moment at joint reversal and peak value was observed after a drop of 0 4m compared to 0 2m and 0 6m The greater mean differences and variability observed in these measures suggest there may have been an enhancement for some individuals However, as individual data was not reported it is not possible to make any conclusions on this matter

The enhancement of kinetic variables following a drop of 0 4m was matched by reduced but not statistically significant amplitude of movement of the BCOM and duration of both the eccentric and concentric phases at that drop height This is consistent with the finding by Bobbert et al (1986a) regarding drop jump technique It is possible that the other two heights (0 2m and 0 6m) did not either provide enough stimulus or were too excessive to allow rapid deceleration of the BCOM following landing, possibly requiring a longer duration and amplitude to dissipate the excessive vGRF upon landing It must be noted that the subjects performed all the jumps in bare feet and it is possible the vGRF experienced was too great to accommodate Lees and Fahmi (1994) found subjects were reluctant to contact the force platform vigorously with bare feet At greater impact forces the human body is obliged to protect it's structures and as a result may lose the ability to recover energy stored in these structure (Less and Fahmi, 1994) Comparisons between drop heights between studies may be misleading due to differing techniques imposing a greater stretch load for comparable drop heights (Young et al, 1999)

2 4 3 Drop jump training studies

Some studies have found that drop jump training enhances vertical jump height in the CMJ (Blatter and Noble, 1979, Brown et al, 1986, Clutch et al, 1983, Gehri et al, 1998, Matavulj et al, 2001) A summary of results of DJ training is outlined in table 2 24 While a degree of enhancement was observed in all studies, enhancements were not statistically significant for all Brown et al (1986) only found a statistical significant enhancement for jumps involving an arm swing, while a 5 5cm enhancement was observed in jumps without the use of arms, the enhancement did not prove to be statistically different The greater variability in jumps without the arms may have been responsible for the lack of statistical significance Clutch et al (1983) found a sıgnıficant ıncrease ın jump heıght for untraıned subjects, but found no sıgnıficant ıncrease ın skılled jumpers

Table 2 24 Effect of drop jump traınıng on CMJ performance

Study	number of subjects	Traınıng	Drop heıght	ΔCMJ heıght	Statıstıcal sıgnıficance
Blatter & Noble (1979)	11 DJ	(3 x 10 DJ) x 3 sessıons x8 weeks	0 86m	2 1 cm	yes
	12 ısokınetıc				
	15 control				
Brown et al (1986)	13 DJ	(3 x 10 DJ) x 2 sessıons x12 weeks	0 45m	5 5cm	no ▲
	13 control				
Clutch et al (1983)	12 subjects	CMJ, DJ30, DJ (75, 110)	0 30m	3 35cm	yes
		2 sessıons x 4 weeks each condıtıon	0 75m & 1 1m	2 97cm	yes
	Skılled 8	(4 x10 DJ) x 2 sessıons x16 weeks	0 75m & 1 1m	3 73cm	no
	Unskılled 8	(4 x10 DJ) x 2 sessıons x16 weeks	0 75m & 1 1m	3 21cm	yes
Gehrı et al (1998)	11 DJ	see note ♣ below	0 40m	2 13cm	yes
	7 CMJ				
	10 control				
Matavulj et al (2001)	DJ 50	(3 x 10 DJ) x 3 sessıons x6 weeks	0 50m	4 8cm	yes
	DJ 100	(3 x 10 DJ) x 3 sessıons x6 weeks	1 00m	5 6cm	yes
	Control				

Note ▲ jumps wıthout the use of arm were not sıgnıficantly enhanced wıth DJ traınıng but jumps wıth the use of the arms were

♣ 2 sessıons per week for 12 weeks, 2 x 8 jumps for first 2 weeks, then 4 x 8 jumps

The dıfferences between studıes and lack of response ın others may have been due to dıfferences ın the way DJs were performed It has been shown that DJ technıque ınfluences the overloadıng of joınt kınetıcs (Bobbert et al, 1987a) Whıle some of the studıes ınstructed ındıvıduals to jump as soon as possıble after landıng (Blatter and Noble, 1979, Matavulj et al, 2001, Young et al, 1999b), no ınstructıon was gıven by Brown et al (1986) In lıght of the findıngs of Bobbert et al (1986a) where some ındıvıduals utılıse a technıque wıth an amplıtude of the movement of the BCOM comparable to the CMJ whıch dıd not overload joınt kınetıcs, ıt ıs possıble that the technıque of some of the ındıvıduals wıthın the Brown et al (1986) study may have been the reason no sıgnıficant enhancement ın jump heıght was observed

In lıght of the potentıal dıfferences ın traınıng effect due to DJ technıque Young et al (1999b) examıned two DJ technıques durıng a sıx week DJ traınıng program The aım of the first technıque was to maxımıse rebound heıght (DJ-H) and the second technıque aımed to achıeve the best combınatıon of rebound heıght and mınımum contact tıme (DJ-H/t) Thırty five subjects traınıng for sıx weeks utılısıng the DJ-H technıque and thırty five utılısıng the DJ-H/t technıque along wıth a control group of thirty five who did not undertake any form of jump training were studied After six weeks of training CMJ height increased by 0 9cm in the DJ-H/t group, however, this enhancement was not found to differ in either the DJ-H or the control group Due to the high number of subjects dropping out of the study in this group the low number of subjects may be partly responsible for lack of statistical significance However, the enhancement in CMJ height achieved is much lower than other studies (Blatter and Noble, 1979, Brown et al 1986, Clutch et al, 1983, Gehri et al, 1998) These studies did have longer training programs but, the amount of jumps is comparable to Matavulj et al (2001) which achieved an enhancement of 4 8cm and 5 6cm for DJ from 0 5m and 1m, respectively It is possible that the greater drop height used provided a greater overload along with the relatively young age of the subjects enabled the greater enhancement observed by Matavulj et al (2001) Additionally, the CMJ used to test enhancement due to training allowed the use of the arms while in the DJ training employed the arms were restricted The only significant enhancement was a greater reactive strength (rebound height/contact time) for the DJ-H/t group, which supports the specificity of training When neuromuscular capacity is altered the coordination pattern needs to be re-optimised (Bobbert and Van Soest, 1994, Nagano and Gerritsen, 2001), it is possible that the coordination pattern for the CMJ utilising the arm swing post training may have been at a sub-optimised level for the enhanced neuromuscular capacity A possible reason for the lack of a significant enhancement in the DJ-H group is that the drop height/technique combination was not enough to induce an overload in the jump kinetics While drop heights used for training where not stated, heights chosen were those that maximised rebound height while the height chosen for the DJ-H/t group maximised the best combination of rebound height and minimum contact time From the data reported for the DJ-H/t group it appears different drop heights may have been used in the training between groups

Methodology

Two forms of analysis to identify factors that correlate with jump performance were undertaken, group analysis (inter-subject) based on differences between individuals and individual subject analysis (intra-subject) based on differences within repetitions of an individual's own movement The group analysis was further divided into two approaches found in the literature for selecting a representative value for each subject A single value per subject was selected two ways, the mean value of the 15 jumps undertaken (G m) and the best jump of the 15 (G b) Comparison of these three approaches was made

3 1 Subjects

Eighteen male subjects (age 23 5±5 3 years and mass 75 2±11kg), who were not currently involved in any form of jump training, participated in the study Ethical approval was received from Dublin City University Information regarding testing was given to all subjects and informed consent was received from all subjects prior to testing All subjects were injury free at the time of the test

3 2 Experimental protocols

Each subject performed three categories of jumps, differing in the amount of eccentric loading the counter movement jump (CMJ) and drop jumps (DJ) from two different heights (0 3m and 0 5m) During the CMJ, the subject lowered their body's centre of mass (BCOM) from a standing upright position by flexing of the lower extremity joints (see section 2 2 for more detailed description) Increased eccentric loading was introduced in the DJ by increasing the amount the velocity of the BCOM had to decrease during the eccentric phase This was achieved by stepping down from boxes whos heights were 0 3m (DJ30) and 0 5m (DJ50) Subjects were instructed to step off the boxes with their dominate foot and land with both feet simultaneously contacting a separate force plate These heights were selected as they were evident in the literature for novice jumpers (Brown et al, 1986, Gehri et al, 1998) Subjects attended on two occasions, the first to familiarise themselves with the protocols, the second involved the collection of data

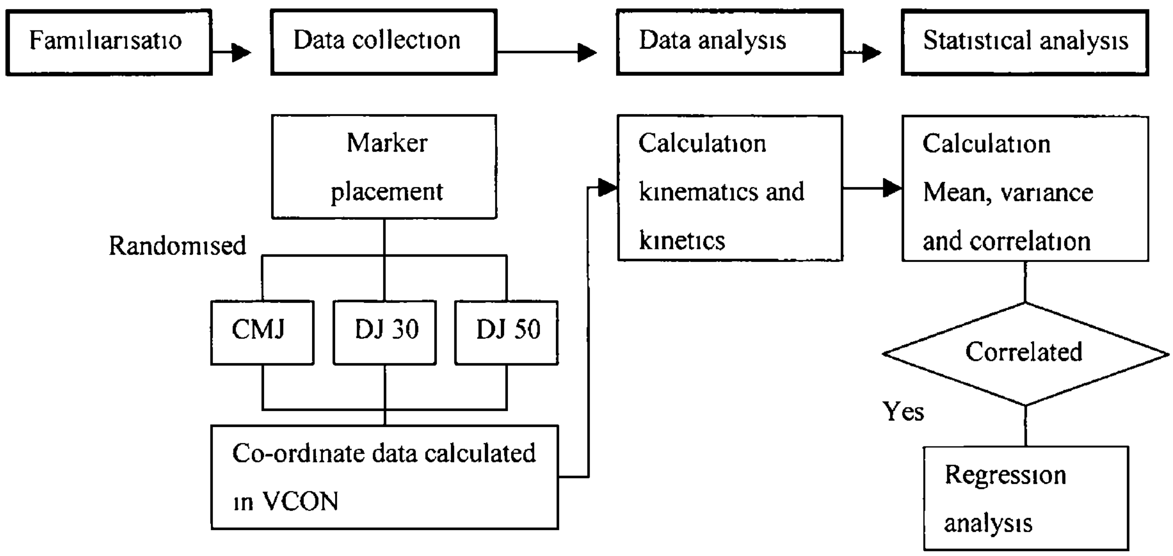


Figure 3 1 Diagram of experimental set-up

Subjects were instructed to jump maximally in all jumps and to jump immediately upon landing during the DJ No additional instructions were given to insure self-selection of technique and elimination of any investor-induced bias into the experiment In all jumps the subject placed their hands on their hips to reduce the use of arms allowing the jump height to be predominately due to the contribution of the leg muscle groups (Bobbert et al, 1986a) Feet were kept parallel with the x-axis of the force platform, restricting motion to the sagittal plane as much as possible Jumps were accepted for analysis when both the subject and the investigator deemed that effort was maximal, take-off and landing occurred in approximately the same position and balance was maintained

Each subject performed 15 acceptable trials under each jump condition This number of trials was found by Moran (1998) using sequential estimation techniques (Hamill and McNiven, 1990) to allow determination of representative jump kinematic and kinetic data The order of each jump conditions were block randomised for each subject to eliminate any condition-sequence interaction A 30 second rest between CMJs and 60 seconds between DJs, and at least 3 minutes between conditions was imposed to reduce the likelihood of fatigue The trial number was recorded to check for samplıng specıfic trends ın the jump heıght achıeved Subjects wore brıef shorts and theır own sports shoes

3 3 Data Acquısıtıon

Locatıons of anatomıcal landmarks were marked on the skın to enable markers to be accurately replaced ın the orıgınal locatıon ın the event of dısplacement durıng testıng Fıve reflectıve sphercal skın mounted markers were place on anatomıcal landmarks of both sıdes of the body - fifth metatarsal joınt, lateral malleolus, lateral femoral epıcondyle of the knee, the most promınent protuberance of the greater trochanter and the glenohumeral joınt ındıcatıng the joınt centres of the toe, ankle, knee, hıp and shoulder, respectıvely (Bobbert et al, 1986) Addıtıonally, a sıxth marker was placed on the heel, level wıth the toe marker (Robertson and Flemıng, 1987) Markers were fixed to the skın usıng medıcal tape

A VICON motıon analysıs (VICON 512 M, Oxford Metrıcs Ltd, England) system was used ın conjunctıon wıth an AMTI force platform mounted ın the ground (BP-600900, AMTI, MA, USA) and AMTI amplıfier VICON software controlled sımultaneous samplıng of motıon and force data at 250Hz Eıght cameras placed evenly around the samplıng arẽa emıtted ınfrared lıght from dıode stroboscopes ın each camera, whıch was reflected back to the cameras by the reflectıve sphercal skın markers Two-dımensıonal co-ordınate data was calculated for each camera and subsequently three dımensıonal co-ordınate data for the captured motıon was calculated by dırect lınear transformatıon (VICON v4 6, Oxford Metrıcs Ltd, England)

Raw co-ordınate data and force data were exported to Excel and subsequently applıed to a number of specıally desıgned ın-house computer programs developed by the author The data was filtered usıng a recursıve second-order low pass butterworth dıgıtal filter (Wınter, 1990) The once filtered data was filtered agaın, but ın the reverse dırectıon of tıme, so as to ıntroduce an equal and opposıte phase lead so as to result ın a net phase shıft of zero (Wınter, 1990) The force plate data was filtered at 70Hz (Moran, 1998) The marker posıtıonal data was filtered at dıfferent values (table 3 1), found usıng resıdual analysıs to mınımıse the root mean square (RMS) of the dıfference between the filtered and unfiltered data over a range of cut-off frequencıes (Moran, 1998) The same cut-off frequency for the toe marker was used for the heel marker as both were not subject to skın movement

Table 3 1 Cut off frequencıes of each joınt marker (Moran, 1998)

	Toe	Heel	Ankle	Knee	Hıp	Shoulder
CMJ	6 62	6 62	7 52	9 21	8 50	6 64
DJ	6 61	6 61	7 48	9 14	8 38	6 41

3 4 Data analysıs

The body was modelled as a rıgıd-body, planar system consıstıng of four segments lınked by frıctıonless hınge joınts The four-segment model of the body has been used ın numerous jumpıng experıments (Aragon-Vargas & Gross, 1997, Hubley and Wells, 1983, Jarıc et al, 1989) The four segments were the foot, shank, thıgh and head-arms-trunk (HAT) separated by the ankle, knee and hıp joınts, respectıvely The lower legs were conceptıonalısed as a 'sıngle equıvalent muscle' model (Robertson and Flemıng, 1987), where the three joınts were vıewed as havıng sıx 'muscles' arranged ın paırs crossıng each joınt, one of each paır representıng tıssues that act as extensors and the others as flexors

The eccentrıc and concentrıc phases of the jump were defined wıth respect to the vertıcal velocıty of the BCOM the eccentrıc phase started wıth the ınıtıatıon of negatıve vertıcal velocıty of the BCOM and ended when the velocıty reached zero and the BCOM was at a mınımum heıght (Hudson, 1988), the concentrıc phase began the ınstant that the BCOM obtaıned posıtıve vertıcal velocıty and ended when the toes lost contact wıth the force platform

The vertical height achieved in the jump was calculated as the vertical difference between the BCOM when standing and at the apex of the jump (Bobbert et al, 1987a) The vertical height of the BCOM (Y_{BCOM}) was calculated as

$$Y_{BCOM} = \sum_{i=1}^{n=4}(R_i * YCOM_i) \qquad \text{Equation 3 1}$$

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

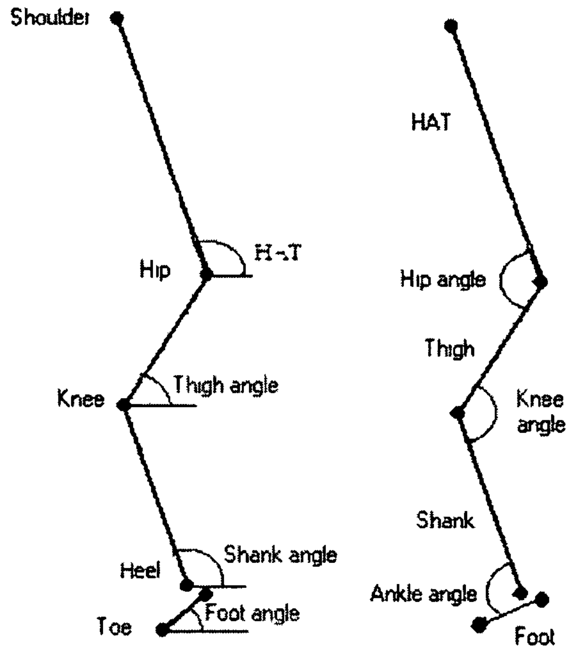


Figure 3 2 Diagram for body segments and angle conventions

Segment angles were calculated in an anti-clockwise direction from the right horizontal with the distal end point of the segment as the origin The segments angles were defined as θ_{foot}, θ_{shank}, θ_{thigh}, θ_{HAT} (for the upper body) (Figure 3 2) The joint angles were calculated as the angle between adjacent segments

$$\theta_{ankle} = \pi - \theta_{shank} + \theta_{foot} \qquad \text{Equation 3 2}$$

$$\theta_{knee} = \pi - \theta_{shank} + \theta_{thigh} \qquad \text{Equation 3 3}$$

$$\theta_{hip} = \pi - \theta_{HAT} + \theta_{thigh} \qquad \text{Equation 3 4}$$

Joint and segment kinetics were calculated by inverse dynamics from kinematic (Johnson and Buckley, 2001, Winter, 1990), ground reaction force data and anthropometric data (table 3 1, pp56-57, Winter 1990) Counter-clockwise moments acting on the segments distal to the joint were considered to be positive Joint reaction forces and moments were calculated as follows

$$F_{xp} = (Mass * A_x) + F_{xd}$$ Equation 3 5

$$F_{yp} = (Mass * A_y) + F_{yd} + (m * g)$$ Equation 3 6

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

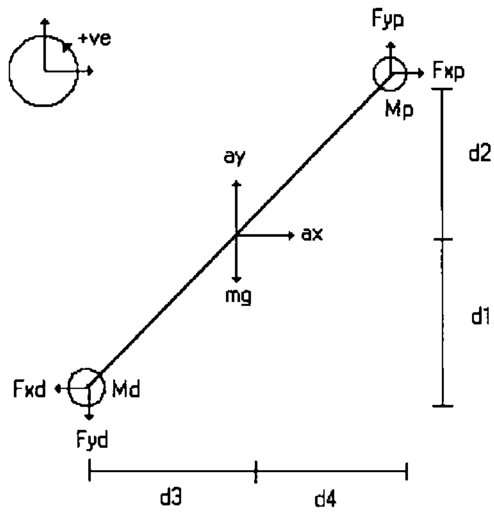


Figure 3 3 Free body diagram for generic body segment

$$M_p = M_d + (F_{xd} * d1) + (F_{xp} * d2) - (F_{yd} * d3) - (F_{yp} * d4) + I\alpha$$ Equation 3 7

Where
Mp = joint moment at proximal
Md = joint moment at distal end
I = moment of inertia about the segment centre of mass
α = segment angular acceleration

Hip extensor, knee extensor and ankle plantar flexor moments were defined as positive (Bobbert et al, 1987a) Net joint muscle power for each joint was calculated as the product of the net muscle moment and the joint angular velocity (Fukashiro and Komi, 1987)

$$P = M_j \omega_j \qquad \text{Equation 3 8}$$

Work done by the muscles during each phase was equal to the integral of power with respect to time (van Ingen Schenau et al, 1985) Integration was performed using the trapezium rule with work calculated for positive and negative phases separately

$$W = \int P\,dt \qquad \text{Equation 3 9}$$

3 5 Variable selection

Kinematic and kinetic variables were evaluated in terms of both magnitude and timing The variables selected for analysis were sub-divided into five main phases

i Kinematics and kinetics during the eccentric phase
ii Kinematics and kinetics at the start of the concentric phase
iii Kinematics and kinetics during the concentric phase
iv Body position at take-off
v Rise in the BCOM after take-off

Additionally, the duration of phases i and iii (above) and the delay between the eccentric and concentric phases, defined as 'coupling' time (Bosco and Komi, 1979), were analysed Kinetic variables were normalised for body mass to control for differences in body weight

Kinematics and kinetics during the eccentric phase

The actions of the muscles during the eccentric phase strongly influences muscle actions during the concentric phase (Bosco et al, 1981, Cavagna et al, 1965) The variables selected for analysis were Peak negative vertical velocity of the BCOM, peak whole body power, peak joint angular velocity, total and individual joint work done and the percentage of total work done at each joint (Bobbert et al, 1987b, Harman et al, 1990)

Kinematics and kinetics at the start of the concentric phase

Kinematics and kinetics at the start of the concentric phase have been shown to affect the kinetics during the concentric phase (Asmussen and Blonde-Petrsen, 1974, Bosco and Komi, 1979) The variables selected for analysis were amplitude of movement of the BCOM, minimum joint angle (joint reversal), force (vGRF) at start of positive phase, the joint moment at joint reversal (Aragon-Vargas & Gross, 1997, Bobbert et al, 1987a, Bosco et al, 1981, Jaric et al, 1989) and coupling time (the time taken for the joint to rotate from one degree prior to joint reversal to one degree after joint reversal) (Bosco et al, 1981)

Kinematics and kinetics during the positive phase

The height the BCOM attains after take-off is dependent primarily on the vertical velocity of the BCOM at take-off Kinematic and kinetic factors which directly and indirectly affect this were examined peak vGRF, peak joint moment, total and individual joint peak power, total and individual joint work done and the percentage of total work done by each joint (Aragon-Vargas and Gross, 1997, Bobbert et al, 1987a, Fukashiro and Komi, 1987, Robertson and Fleming, 1987, Rodano and Roberto, 2002)

Body position at take-off

The height the BCOM attains post take-off is dependent on the kinetic and potential energy at take-off (Bobbert and van Ingen Schenau, 1988) The potential energy is determined by how high the BCOM is located at take-off, therefore the vertical height difference of BCOM at take-off from that of standing was examined

Rise in the BCOM after take-off

Jump height was defined as the difference between the peak height the BCOM attained at the apex of the jump and that at standing (Bobbert et al, 1987a) This was taken as the measure of jump performance

Coordination is a major factor in proficient execution of a motor task and refers to the timing and sequence of segmental movements Coordination was analysed at the joint level by examining the time delay between key events of adjacent joint pairings hip and knee, knee and ankle The following variables were examined initiation of joint extension (Rodacki et al, 2002), peak joint angular velocity (Jensen et al, 1994), peak joint moment and peak joint power (Bobbert and van Ingen Schenau, 1988) Absolute timing difference between events was taken In addition to negate the effect of the total duration of the movement, timing delays were also examined as a proportion of total concentric phase duration (relative timing) (Rodacki et al, 2001)

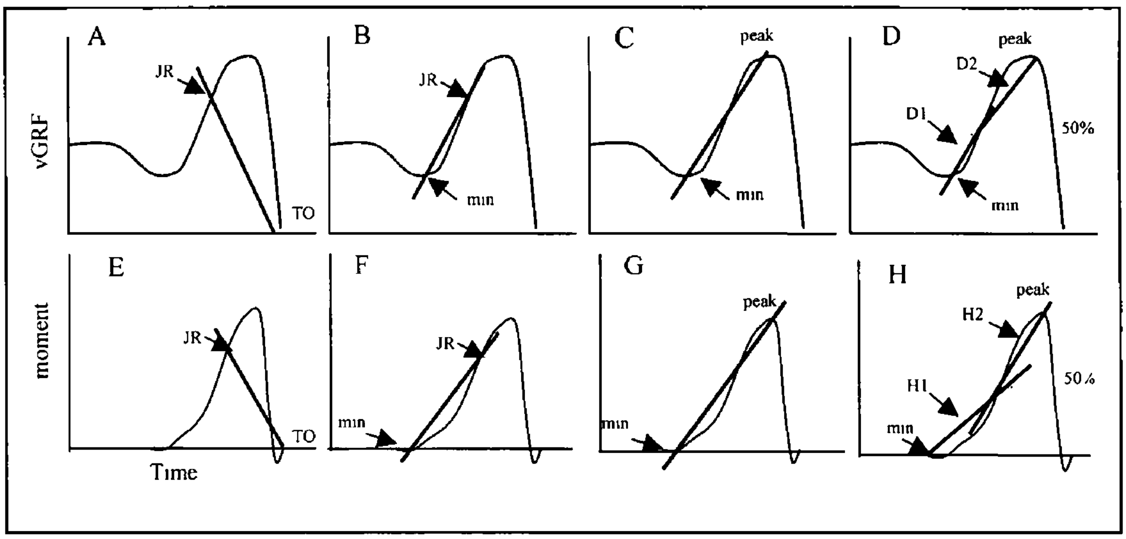


Figure 3 4 Measures of rate of force development

The rate of force development (RFD) was calculated as the rate of change in the magnitude of joint moment or vGRF over selected time intervals The rate of power development was calculated for individual joints as the increase in joint power in the first 60ms of the concentric phase The selected intervals (Figure 3 4) were -

- From joint reversal (or start of concentric phase) to the instant of take-off (A and E)
- From the minimum vGRF to joint reversal (or the start of concentric phase) (B and F)
- From the instance of minimum vGRF to peak moment (or peak vGRF) (C and G)
- From the instance of minimum vGRF to 50% peak moment (or peak vGRF) (D1 and H1)

- From 50% peak moment/vGRF to peak moment (or peak vGRF) (D2 and H2)

Since isometric tests examine the RFD without eccentric loading, it was of interest to determine if a relationship exists between jump height and neuromuscular output in the concentric phase only in the CMJ From JR to peak force is the only portion of the jump where force is developed by solely a concentric contraction However, the interval from JR to peak joint moment (or vGRF) was not included because for many subject these two events occurred simultaneously or the peak occurred prior to JR

2 6 Statistical analysis

Descriptive statistics (mean magnitude and variance) were calculated for the jump height achieved and each biomechanical jump parameter at both a group level (G b and G m) and individual subject level Pearson product moment correlations were performed between the biomechanical parameters and the jump height achieved An $\alpha = 0\ 05$ level was adopted for statistical significance Bivariate regression techniques were applied to calculate the slope of the relationship to jump mechanical parameters found to be significantly correlated with jump height achieved The residuals from the bivariate analysis were plotted against the predicted values to verify that the basic assumptions of normality were met The influence of outliners was assessed by visual observation of plotted values against jump height and in borderline cases using Cook's distance, outliers where subsequently omitted from analysis Visual examination of scatter plots of each variable and jump height was undertaken to determine weather a linear pattern was present, and was verified by plotting the residuals against the predicted values from the bivariate regression analysis (Montgomery, 1991) Hypothesis concerning differences between jump conditions were tested using a two-way repeated measures analyses of variance (ANOVA) in the case of group analyse and a one-way repeated measures ANOVA in the case of individual analyse An $\alpha = 0\ 05$ level was adopted for statistical significance Where statistical differences were observed a Tukey's post-hoc analysis was employed All statistical analysis was performed using SPSS (version 10)

Results

The group mean, the inter-subject variability and the mean intra-subject variability for the biomechanical parameters of the CMJ are detailed below Results of correlation analysis at the group level using both the mean magnitude for each of the 18 subjects (G m), and the data from each subject's best performance (G b) are presented In addition, individual subject correlation analyse utilising all 15 jumps undertaken by each subject are presented Where no correlation is reported, that parameter was not found to be correlated with jump height (α = 0 05 significance level The data is sectionalised in the following phases

(i) the eccentric phase

(ii) the transition phase between the eccentric and concentric phases

(iii) the concentric phase

Differences in jump kinetics between CMJ and DJ from 0 3m and 0 5m will be outlined to investigate the possible use of drop jumping as a means of stressing specific neuromuscular parameters for training purposes Time history of selected joint variables (angle, angular velocity, moment and power) for a CMJ of a representative subject is presented in Figure 4 1

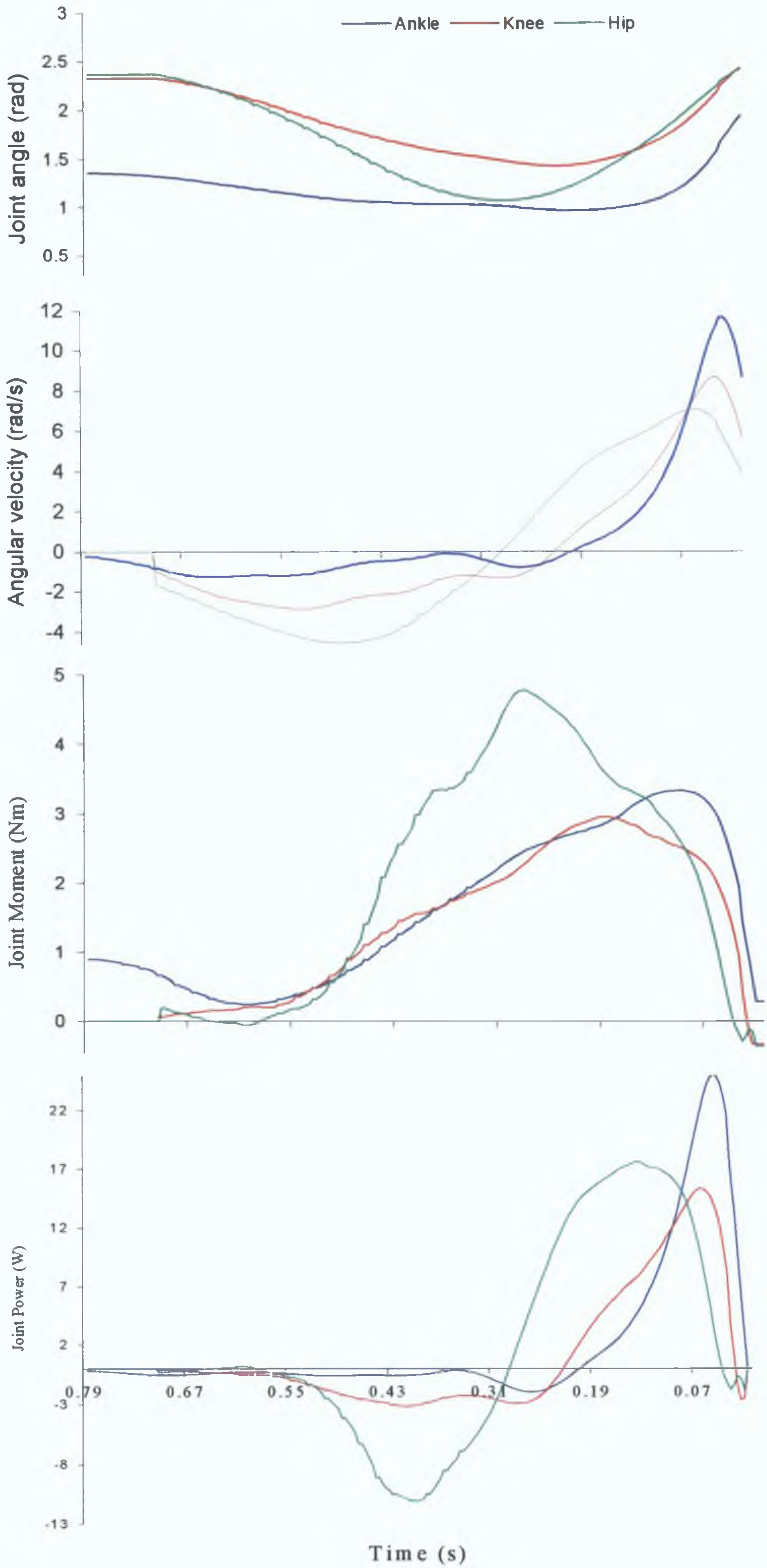


Figure 4.1 Joint time histories for a representative subject.

4 1 Variability and the relationship with jump performance

The following section outlines the extent to which the kinematic and kinetic variables varied both between subjects (inter-subject) and within repeated individual performances (intra-subject) Variability is presented in the units of the variable (standard deviation, SD) and standardised as a percentage of the variable's mean (coefficient of variation CV) These are presented along with the overall group mean Results of bivariate statistical analysis for the relationship between the magnitude of the kinematic and kinetic parameters and the magnitude of jump height are also presented All correlations where an increase in jump height was observed with an increase in the magnitude of a parameter are reported as positive Analysis at the group level used inter-subject data based on both the mean values (G m) and values from the best jump (G b) Where no correlation coefficient and level of significance are reported in a table, this indicates that no significant correlation was evident ($\alpha = 0\ 05$) This gives a visual representation of the distribution of significant parameters Subjects were ranked according to their mean CMJ jump height (e g subject 1 greatest mean jump height, subject 18 lowest mean jump height)

Kinetics during the negative phase

Table 4 1 outlines the mean magnitude observed for peak negative velocity of the BCOM, the duration of the eccentric phase, the peak negative whole body power and the total negative work done during the eccentric phase Variability was notably lower at the individual subject level than at the group level, with the exception of whole body peak power where no notable difference was evident

Table 4 1 Mean and variance values of whole body kinematics and kinetics for the group and average variance for individuals during the eccentric phase

	Group			Individual	
	Mean	SD	CV	Mean SD	Mean CV
Peak negative velocity (ms^{-1})	-1 03	0 32	-30 8	0 09	-9 3
Phase Duration (s)	0 54	0 19	34 8	0 08	15 6
Peak Power (W)	-19 78	8 03	-40 6	7 30	-39 1
Work done (J)	-2 45	0 60	-24 5	0 21	-9 4

Note SD Standard deviation
CV Coefficient of variability

Table 4 2 below details the correlation coefficient (r) and level of statistical significance (p) for the relationship between jump height and the peak negative vertical velocity of the BCOM, the duration of the eccentric phase, the peak negative whole body power and the total negative work done during eccentric phase

Table 4 2 Correlation (r) and level of significance (p) for the relationship between jump height and whole body kinematics and kinetics during the eccentric phase

	Peak velocity		Phase duration		Peak power		Work done	
	r	p	r	p	r	p	r	p
G b	0 52	0 026						
G m	0 60	0 008	-0 47	0 050	0 58	0 010		
1	0 82	0 007					0 53	0 036
2							0 53	0 035
3							0 61	0 009
4			0 65	0 007			0 69	0 003
5							0 68	0 003
6								
7	0 60	0 036						
8	0 57	0 035	-0 67	0 007				
9			-0 57	0 022				
10								
11								
12								
13								
14								
15								
16								
17								
18	0 84	0 008	-0 58	0 019			0 80	< 0 001

Note G b Group data based on the best performance of each individual
G m Group data based on the mean values of all 15 jumps for each individual

Peak velocity, phase duration and peak power were all found to be correlated with jump height at a group level (inter-subject) when the mean values of each subject's 15 jumps (G m) were analysed, while only peak velocity was correlated at a group level when the best jump by each subject was analysis (G b) In contrast to the group analysis, only three of the 18 subjects had significant correlations between jump height and either peak velocity or phase durations at an individual subject level (intra-subject) Peak power was not found to be correlated with jump height for any individuals Total work done during the eccentric phase did not provide a means of differentiating between individuals at a group level with respect to mean jump height, however a correlation was apparent for six subjects at an individual level

Table 4 3 outlines the mean values for the peak angular velocity and the total work done during the eccentric phase for each joint Measures of inter-subject variability and mean values of intra-subject variability are presented Greater variability was observed between individuals (inter-subject) compared to within an individuals own performance (intra-subject) In addition, greater variability between individuals was observed at the ankle joint compared to the knee and hip joints This also held true at the intra-subject level for the work done at the ankle, but peak angular velocity at the ankle was not seen to be more variable than at the other joints

Table 4 3 Mean and variance values of joint kinematics and kinetics during the eccentric phase for the group and average variance for individuals

	Group			Individual	
	Mean	SD	CV	Mean SD	Mean CV
Ankle peak velocity (rad s^{1})	-1 37	0 76	-55 6	0 23	-15 5
Knee peak velocity (rad s^{1})	-2 64	0 90	-34 2	0 23	-14 3
Hip peak velocity (rad s^{1})	-3 40	0 86	-25 4	0 34	-10 5
Ankle work done (J kg^{1})	-0 29	0 18	-61 8	0 07	-25 6
Knee work done (J kg^{1})	-0 91	0 38	-42 5	0 11	-12 8
Hip work done (J kg^{1})	-1 25	0 47	-37 8	0 18	-16 5

Table 4 4 details the correlation coefficient (r) and level of significance (p) for the relationship between jump height and the peak angular velocity, and the amount of negative work done at the ankle, knee and hip joints during the eccentric phase At a group level only peak hip angular velocity was significantly correlated with jump height and only when mean values (G m) were employed in the analysis This relationship was also evident at an individual level in four of the 18 subjects While angular velocity at other joints were not significantly correlated with jump height at a group level, significant correlations were observed for two and three individuals for the ankle and knee joints, respectively Total negative work done was not correlated with jump height at the group level for any joint Work done at the ankle was only correlated for one individual, while work done at the knee and hip joints were correlated with jump height for five and seven individuals, respectively Three of the five individuals that exhibited a correlation between knee negative work done and jump height had a positive correlation, while six of the seven had a positive correlation in the case of the hip joint

Table 4 4 Correlation (r) and level of significance (p) for the relationship between jump height and selected segmental parameters during eccentric phase

	Ankle peak velocity		Knee peak velocity		Hip peak velocity		Ankle work done		Knee work done		Hip work done	
	r	P	r	p	r	p	r	p	r	p	r	p
G b												
G m					0 64	0 004						
1												
2			0 58	0 036								
3											0 64	0 005
4									0 59	0 016	0 67	0 004
5					0 68	0 004			0 68	0 004	0 68	0 004
6											0 53	0 034
7												
8			0 62	0 013	0 61	0 004						
9									-0 56	0 023		
10											-0 62	0 015
11												
12												
13												
14	0 59	0 016			0 59	0 016			-0 54	0 029	0 57	0 021
15												
16												
17												
18	0 52	0 045	0 77	<0 001	0 83	<0 001	-0 51	<0 001	0 84	<0 001	0 82	<0 001

Kinematics and kinetics at start of concentric phase

Table 4 5 below details the mean amplitude of the BCOM, the vertical ground reaction force (vGRF) at the start of the concentric phase, and the joint angles and instantaneous joint moments at joint reversal (JR) for each joint The point where the BCOM reversed its vertical direction was taken to be the start of the concentric phase of the whole body The point where the rotation of the joint changed direction, called joint reversal (JR), was taken to represent the start of the concentric phase for an individual joint Measures of inter-subject and mean values of intra-subject variability are presented Inter-subject variability was approximately three times the intra-subject variability The angle of the hip at JR was more variable at both inter-subject and intra-subject levels compared to the ankle and knee joints, suggesting less of a consistency in temporal strategies employed at the hip

Table 4 5 Mean and variance values of whole body and segmental kinematics and kinetics for the group and average variance for individuals at the start of the concentric phase

	Group			Individual	
	Mean	SD	CV	Mean SD	Mean CV
Amplitude (m)	0 33	0 07	20 2	0 02	6 6
vGRF (N kg^{1})	10 72	2 71	25 3	0 84	8 5
Ankle angle (rad)	0 96	0 09	9 0	0 03	2 6
Knee angle (rad)	1 38	0 25	18 1	0 05	4 2
Hip angle (rad)	1 11	0 30	27 3	0 09	9 6
Coupling time ankle (s)	0 12	0 04	33 8	0 03	27 6
Coupling time knee (s)	0 09	0 03	29 7	0 02	18 6
Coupling time hip (s)	0 07	0 02	24 9	0 01	10 0
Ankle moment (N m kg^{1})	2 57	0 83	32 4	0 34	14 1
Knee moment (N m kg^{1})	2 78	1 02	36 6	0 32	12 3
Hip moment (N m kg^{1})	3 44	1 00	29 1	0 35	11 2

Table 4 6 details the correlation coefficient (r) and level of significance (p) for the relationship between jump height, and amplitude of movement of the BCOM, joint angles at JR, the vGRF at the start of the concentric phase and the joint moments at JR A negative correlation between jump height and joint angle at JR suggests a greater joint flexion was observed in jumps of greater height While no direct measure of joint range of motion (ROM) was taken, starting position was standardised, therefore a lesser joint angle at JR can be assumed to be a greater ROM None of the kinematic parameters outlined were significantly correlated with jump height at the group level However, at the individual level five subjects had a significant correlation between jump height and amplitude of movement, while two, six and five had significant correlations between jump height and the ankle, knee and hip angles at JR, respectively The majority of correlations between jump height and the amplitude of movement were positive, suggesting greater amplitude occurred on average in jumps of greater height, while there were predominately negative correlations between jump height and the joint angle at JR, suggesting greater joint flexion was evident in jumps of greater height The exception to this were subjects nine and 14, for subject nine the opposite relationship was observed for both amplitude of movement of the BCOM and knee angle, additionally for subject 14 knee angle was positively correlated with jump height, suggesting jumps greater height also had on average less knee flexion

The vGRF at the start of the concentric phase was found to be correlated with jump height at a group level when the mean of each subjects 15 jumps were used in the analysis (G m) At a segmental level, only the ankle joint instantaneous moment at JR was marginally correlated with jump height at a group level (G m and G b) The number of significant correlations at an individual level was three and four for the moment at ankle and hip joints at JR respectively, while no significant correlation between jump height and the moment at the knee joint at JR was found for any individual At the group level coupling time was only found to be correlated with jump height at the hip joint (G m r = -0 48, p = 0 43) At an individual level, the coupling time of the ankle joint was found to be correlated with jump height for a single individual (subject 1 r = -0 56, p = 0 025) and at the hip joint for two (subject 14 r = -0 53, p = 0 035, subject 18 r = -0 73, p = 0 002)

Table 4 6 Correlation (r) and level of significance (p) for the relationship between jump height and kinematic variables at the start of the concentric phase

	Amplitude		Ankle ROM		Knee ROM		Hip ROM		vGRF at start of phase		Ankle moment at JR		Knee moment at JR		Hip moment at JR	
	r	p	r	p	r	p	r	p	r	p	r	p	r	p	r	p
G b											0 47	0 050				
G m									0 47	0 048	0 49	0 038				
1																
2											0 68	0 004				
3	0 66	0 004					0 69	0 002								
4	0 69	0 003			0 64	0 007	0 67	0 005								
5	0 76	0 001	0 53	0 034	0 64	0 008	0 80	<0 001			-0 60	0 015				
6																
7																
8									0 53	0 041						
9	-0 56	0 023			-0 57	0 021									0 62	0 01
10																
11																
12																
13									0 64	0 011	0 57	0 027			0 64	0 015
14					-0 57	0 021	0 63	0 009							0 71	0 005
15			0 52	0 047	0 64	0 014										
16																
17																
18	0 84	<0 001			0 80	<0 001	0 84	<0 001							0 91	<0 001

Note JR joint reversal
vGRF Vertical ground reaction force

Kinematics and kinetics during the concentric phase

Table 4 7 below outlines the mean rise in the BCOM from standing to take-off ($BCOM_{s\ to}$), the duration of the concentric phase, the peak vGRF, the peak whole body power and the total positive work done during the concentric phase Measures of inter-subject and mean values of intra-subject variability are presented As can be seen from table 4 7 greater variability between subjects for whole body kinetics during the concentric phase exists compared to intra-subject variability

Table 4 7 Group mean, SD and CV and individual SD and CV for whole body kinematics and kinetics for during the concentric phase

	Group			Individual	
	Mean	SD	CV	SD	Mean CV
BCOMs-to (m)	0.11	0.02	13.0	0.01	8.8
Phase duration (s)	0.29	0.06	19.8	0.02	6.6
Peak vGRF ($N\ kg^{-1}$)	11.88	2.07	17.4	0.57	5.0
Peak Power ($W\ kg^{-1}$)	48.94	6.92	14.1	1.71	3.5
Work Done ($J\ kg^{-1}$)	6.02	0.83	13.9	0.33	6.0

Note BCOMs-to Difference in height of BCOM between standing and take-off
Peak vGRF Peak vertical ground reaction force

Table 4 8 shows the correlation coefficient and corresponding level of statistical significance for the relationship between jump height and the $BCOM_{s\ to}$, the duration of the concentric phase, the peak vGRF, the peak whole body power and the total positive work done during the concentric phase The $BCOM_{s\ to}$, the duration of the concentric phase, the peak vGRF and the peak whole body power were not correlated with jump height at a group level but were significantly correlated with jump height for six, five and three individuals, respectively In contrast, the peak whole body power and the total work done were positively correlated with jump height at both the group level (G m and G b) and for nine and eleven individuals, respectively The positive correlation between jump height and phase duration for four of the five individuals suggests jumps of greater height also had on average a longer concentric phase For one individual (subject 9) a negative correlation between jump height and the duration of the concentric phase was evident, suggesting jumps of greater height had shorter concentric phases on average for this individual

Table 4 8 Correlation (r) and level of significance (p) between jump height and whole body kinematics and kinetics during the concentric phase

	BCOMs-to		Phase duration		Peak vGRF		Peak Power		Work Done	
	r	p	r	p	r	p	r	p	r	p
G b									0 50	0 035
G m							0 56	0 014	0 48	0 043
1									0 73	0 001
2									0 66	0 005
3									0 83	<0 001
4			0 66	0 009					0 83	<0 001
5			0 71	0 002	-0 66	0 006			0 77	0 001
6	0 62	0 01					0 72	0 002	0 80	<0 001
7							0 63	0 009	0 67	0 005
8										
9			-0 56	0 024			0 77	<0 001		
10	0 80	<0 001					0 61	0 016		
11							0 69	0 005		
12							0 74	0 002	0 52	0 044
13	0 71	0 003			0 62	0 013				
14			0 79	<0 001			0 81	<0 001	0 86	<0 001
15	0 65	0 009					0 83	<0 001	0 75	0 001
16							0 72	0 001		
17	0 54	0 037								
18	0 67	0 005	0 67	0 004	-0 68	0 004			0 86	<0 001

Table 4 9 below outlines the mean values for the peak joint moments and powers and the amount of work done at each joint during the concentric phase Measures of inter-subject variability and mean values of intra-subject variability are presented Inter-subject variability was over two-fold that of intra-subject variability In addition, comparison to the equivalent whole body measures outlined in table 4 7 reveal there was also a greater than two-fold increase in variability of segmental measures

Table 4 9 Mean and variance of segmental kinematics and kinetic for group and average variance for individuals during the concentric phase

	Group			Individual	
	Mean	SD	CV	Mean SD	Mean CV
Peak ankle moment (N m kg^{-1})	3 10	0 56	18 1	0 23	7 5
Peak knee moment (N m kg^{-1})	3 15	0 85	26 9	0 34	11 2
Peak hip moment (N m kg^{-1})	3 74	0 89	23 7	0 29	8 4
Peak ankle power (W kg^{-1})	22 11	4 98	22 5	2 04	9 2
Peak knee power (W kg^{-1})	14 42	4 10	28 4	1 63	11 5
Peak hip power (W kg^{-1})	13 71	3 80	27 7	1 42	11 0
Ankle work done (J kg^{-1})	2 01	0 42	21 1	0 19	9 2
Knee work done (J kg^{-1})	1 68	0 57	34 2	0 19	11 7
Hip work done (J kg^{-1})	2 33	0 81	34 8	0 29	13 8

Table 4 10 details the correlation coefficient and corresponding level of statistical significance for the relationship between jump height and peak moment, peak power and positive work done at all three joints Both peak ankle moment and peak ankle power were found to be correlated with jump height at the group level (G m and G b) and at an individual subject level for six and five individuals, respectively Five of the six individuals exhibited a positive correlation between jump height and peak ankle moment, as inline with the group analysis, while subject 18 had a negative correlation Peak knee moment was not found to be significantly correlated with jump height at a group level, but two subjects had individual negative correlations These two individuals also exhibited a positive relationship between knee angle at JR and jump height outlined in table 4 6 Peak knee power was significantly correlated with jump height at the group level but only when the best jumps were used in the analysis (G b) and also for two individuals, but contrasting relationships were observed (subject 4 r = -0 50, subject 15 r = 0 66) Neither peak hip moment nor power were significantly correlated at a group level with jump height but was significantly correlated at an individual level for five and six individuals, respectively

The amount of positive work done at the ankle joint was positively correlated with jump height at a group level (G m and G b) and for eight individuals, suggesting jumps of greater height also had more work was done on average Both knee and hip work done were not significantly correlated at a group level (G m and G b), however, hip work done was found to be positively correlated with jump height for six individuals While a significant correlation between knee work done and jump height was evident for four individuals, contrasting relationships were observed For two individuals jumps of greater height had more work done at the knee on average, while the opposite was true for a further two subjects The two individuals whose knee work done was negatively correlated with jump height, also had a positive correlation between jump height and knee joint angle at JR, and between jump height and negative knee work done (tables 4 6 and 4 4 respectively), suggesting a lesser knee joint ROM and less knee work was done in jumps of greater height

Table 4 10 Correlation (r) and level of significance (p) between jump height and segmental kinematics and kinetics during the concentric phase

	Peak ankle moment		Peak knee moment		Peak hip moment		Peak ankle power		Peak knee power		Peak hip power		Ankle work done		Knee work done		Hip work done	
	r	p	r	p	r	p	r	p	r	p	r	p	r	p	r	p	r	p
G b	0 48	0 042					0 53	0 025	0 52	0 028			0 61	0 007				
G m	0 51	0 030					0 58	0 012					0 58	0 012				
1	0 59	0 020											0 58	0 018				
2	0 55	0 026											0 58	0 020				
3					0 55	0 021											0 70	0 002
4									-0 50	0 048							0 81	<0 001
5																	0 65	0 007
6							0 64	0 008			0 57	0 022	0 59	0 016			0 55	0 027
7					0 56	0 025							0 58	0 018				
8											0 60	0 018						
9			-0 59	0 015			0 64	0 008			0 54	0 029			-0 69	0 003		
10																		
11	0 56	0 031																
12							0 70	0 003					0 70	0 004				
13					0 69	0 007							0 70	0 004				
14	0 65	0 006			0 57	0 021	0 73	0 001			0 73	0 001	0 86	<0 001	-0 56	0 026	0 71	0 002
15	0 59	0 021					0 57	0 026	0 66	0 007			0 68	0 005	0 69	0 005		
16											0 58	0 015						
17																		
18	-0 65	0 006	-0 66	0 005	0 93	<0 001					0 85	<0 001			0 67	0 004	0 85	<0 001

The total amount of work done is the summation of the amount of work done at the individual joints Alteration in the relative contribution of each joint to total work done may affect jump height, table 4 11 outlines for all subjects the average percentage contribution of each joint Differences in the relative contribution of each joint to total work done are evident between subjects For example, for subject two the relative contribution of the ankle joint to total work done was 49 5% but was only 22 8% for subject nine, the hip joint contribution ranged from 56 5% for subject 16 to 14 0% for subject five No correlation was observed at the group level (G m and G b) between jump height and the relative contributions of each joint to total work done At an individual level correlations are outlined in table 4 11, when no value is present a non-significant correlation was observed

Table 4 11 Percentage of total work done by each joint and correlation with jump height

	% work ankle	% work knee	% work hip	% ankle r	% knee r	% hip r
G m	33 8	27 9	38 3			
G b	34 8	26 7	38 5			
1	32 9	27 0	40 1			
2	49 5	21 2	29 3			
3	28 8	25 4	45 8	-0 53		0 48
4	27 4	20 8	51 8	-0 56		0 71
5	41 9	44 1	14 0			0 54
6	52 8	32 4	14 8			
7	34 0	31 2	34 8			
8	31 9	22 0	46 1	-0 60		0 60
9	22 8	38 8	38 4	0 57	-0 69	0 63
10	41 5	26 5	32 0			
11	29 5	24 3	46 2			
12	26 1	38 5	35 4	0 56		
13	28 0	28 0	44 0			
14	33 9	37 3	28 8			
15	36 5	19 5	44 0	0 73	-0 77	0 55
16	28 7	14 8	56 5			
17	29 4	14 8	55 8	0 45		
18	33 2	35 6	31 2	-0 78	-0 84	0 86

4 1 1 Jump predictors based on group analysis

Investigation into which biomechanical parameters determine jump performance has predominantly been focused on a group level The biomechanical parameters correlated at a group level may differ to those found at an individual level Table 4 12 details the slope and level of significance of the linear relationship for variables that exhibited a significant correlation with jump height at a group level (G m and G b) and the number of subjects that exhibited a correlation with jump height for these parameters at an individual level

Table 4 12 Descriptions of relationship between jump height and mechanical parameters that where correlated at a group level and number of individuals that also exhibited a correlation with jump height for these parameters

		G b	G m	Number of individuals with sig correlation (p<0 05)
Peak whole body power concentric phase (W)	Slope	0 003	0 005	9
	p-value	0 010	< 0 001	
Peak negative velocity of BCOM (m s^{1})	Slope	-0 070	-0 087	4
	p-value	0 026	0 008	
Peak power eccentric phase (W)	Slope		0 000	0
	p-value		0 015	
Whole body positive work done (J)	Slope	0 027	0 026	11
	p-value	0 035	0 043	
vGRF at start on con phase (N)	Slope		0 008	2
	p-value		0 048	
Duration Eccentric phase (s)	Slope		-0 114	4
	p-value		0 050	
Peak negative hip angular velocity (rad s^{1})	Slope		-0 030	4
	p-value		0 004	
Positive ankle work done (J)	Slope	0 058	0 062	8
	p-value	0 007	0 012	
Peak Ankle Power (W)	Slope	0 004	0 005	5
	p-value	0 025	0 012	
Peak Ankle moment (Nm)	Slope	0 030	0 042	6
	p-value	0 042	0 030	
Ankle moment @ JR (rad)	Slope	0 025	0 027	3
	p-value	0 050	0 038	
Peak knee power (W)	Slope	0 006		0
	p-value	0 028		
Hip coupling time (s)	Slope		-1 309	2
	p-value		0 043	

4.1.2 Selection of jump parameter to alter to enhance jump height

When making a decision of which biomechanical parameter to train, four questions must be taken into consideration. Firstly, how strong is the relationship between the biomechanical factor and jump height? Secondly, how much will a change in the biomechanical factor increase jump height? Thirdly, by how much can the biomechanical factor be trained? Fourthly, what is the magnitude of biomechanical factor for the individual relative to the group mean? The strength of the relationship between a biomechanical factor and jump height is revealed by the correlation coefficient. The amount, by which an increase in one unit of a parameter corresponds to an increase in jump height, is determined by the slope of the relationship. While the standard deviation and the CV don't directly answer how much the factor can be varied they provide a measure into how much the factor varied.

The four parameters outlined in table 4.13 provide good examples of differing relationships regarding variability and the relationship between changes in the parameter and jump height. Where no slope for an individual is present, that parameter was not found to be significantly correlated with jump height for that individual. In order to compare slopes across parameters of differing units the 'Adjusted slope' was taken as the slope divided by the mean of the parameter. As can be observed from the CV and the mean absolute value of the slope, hip negative work done exhibits a relatively large variability and a steep slope on average. In contrast, peak ankle moment has a relatively small variance and a gentler gradient for the relationship of the change with jump height. Peak knee angle at JR and peak hip power provide examples of low variability/steep slope and high variability/shallow slope, respectively. However, these patterns did not hold for all individuals. For the knee angle at JR, which in general had a steep slope and low variability, different relationships were demonstrated at an individual level. Subject 15 had a low variance and steep slope, while subject four had a large variance and a gentler slope.

Table 4 13 Mean, variance and slope for selected parameters to highlight issue regarding selection parameters to altering to achieve increases in jump height

	Hip negative work done (J)				Knee angle at JR (radian)				Peak ankle moment (Nm)				Peak hip power (W)			
Subject	Mean	SD	CV	slope	Mean	SD	CV	slope	Mean	SD	CV	slope	Mean	SD	CV	slope
1	0 54	0 15	27 8		1 14	0 03	2 6		3 39	0 35	10 3	0 050	14 14	1 48	10 5	
2	0 36	0 12	33 3		1 65	0 04	2 4		4 49	0 12	2 7	0 021	13 44	1 02	7 6	
3	0 66	0 18	27 3	-0 048	1 44	0 04	2 8		3 21	0 17	5 3		21 64	1 77	8 2	
4	0 70	0 32	45 7	-0 024	1 60	0 09	5 6	-0 081	2 62	0 22	8 4		18 79	1 26	6 7	
5	0 24	0 07	29 2	-0 133	1 50	0 05	3 3	-0 161	2 80	0 22	7 9		7 11	0 79	11 1	
6	0 22	0 08	36 4	-0 121	1 46	0 04	2 7		4 01	0 21	5 2		8 36	0 79	9 4	0 013
7	0 55	0 12	21 8		1 49	0 04	2 7		3 13	0 23	7 3		13 03	1 65	12 7	
8	0 62	0 16	25 8		1 54	0 11	7 1		3 37	0 16	4 7		15 72	1 04	6 6	0 003
9	0 43	0 17	39 5		0 90	0 04	4 4	0 053	2 21	0 47	21 3	0 056	11 55	1 24	10 7	0 005
10	0 38	0 33	86 8		1 35	0 07	5 2		3 65	0 20	5 5		13 47	1 33	9 9	
11	0 65	0 24	36 9		1 45	0 06	4 1		2 84	0 31	10 9		16 83	1 80	10 7	
12	0 49	0 14	28 6		0 88	0 04	4 5		3 39	0 48	14 2		11 12	1 68	15 1	
13	0 52	0 13	25 0		1 30	0 05	3 8		2 65	0 14	5 3		14 02	1 17	8 3	
14	0 34	0 31	91 2	-0 087	0 98	0 05	5 1	0 223	2 67	0 15	5 6	0 094	10 52	2 63	25 0	0 013
15	0 61	0 09	14 8		1 67	0 02	1 2	-0 464	3 21	0 17	5 3	0 050	14 19	0 93	6 6	
16	0 73	0 18	24 7		1 57	0 05	3 2		2 82	0 18	6 4		18 35	1 16	6 3	0 004
17	0 64	0 26	40 6		1 56	0 05	3 2		2 74	0 18	6 6		15 51	2 33	15 0	
18	0 42	0 37	88 1	-0 063	1 40	0 09	6 4	-0 250	2 64	0 25	9 5	-0 073	8 94	1 91	21 4	0 130
Mean			40 2	0 080			3 9	0 205			7 9	0 057			11 2	0 028
Adjusted slope				0 157				0 149				0 018				0 002

Note Mean of slope, calculated from absolute values of slope
Adjusted slope = slope / mean

4 1 3 Variability and parameter identification

Table 4 14 details the mean jump height, standard deviation and range of jump heights observed for each individual Also included is the average coefficient of variability (CV) of all the kinematic and kinetic parameters examined, the number of significant relationships with jump height observed for each individual and of those the number them that are also evident in the group model, irrespective of the sign of the relationship, are presented

Table 4 14 Mean, standard deviation and range of jump height observed for each individuals and the number of significant relationships observed

	Jump Height (m)			Variables		
Subject	Mean	SD	Range	Mean CV	Number of significant	Number also in group model
1	0 51	0 01	0 03	7 5	4	3
2	0 50	0 01	0 05	9 3	7	5
3	0 49	0 01	0 05	8 3	7	1
4	0 49	0 01	0 05	11 7	11	2
5	0 46	0 01	0 04	9 2	13	2
6	0 43	0 02	0 07	8 4	8	4
7	0 42	0 02	0 06	11 3	5	4
8	0 42	0 01	0 03	8 0	5	4
9	0 42	0 01	0 04	11 9	10	2
10	0 42	0 02	0 05	9 1	3	1
11	0 41	0 02	0 08	14 5	2	2
12	0 41	0 02	0 06	10 9	4	4
13	0 40	0 02	0 06	12 0	6	3
14	0 40	0 02	0 08	10 3	18	7
15	0 39	0 01	0 06	8 9	10	5
16	0 38	0 01	0 03	11 4	2	1
17	0 36	0 01	0 04	10 4	1	0
18	0 34	0 03	0 11	15 9	21	5
Mean	0 43	0 02	0 06	10 5	7 6	3 0

The range in jump heights observed was found to be significantly correlated with the number of significant variables found for an individual (r = 0 59, p = 0 009) However, no significant correlations were found when the standard deviation of jump height was examined This suggests that individuals who displayed a greater range of jump heights during the experiment also exhibited a greater number significant correlations between jump height

4 2 Coordination and jump performance

Table 4 15 details the mean timing delay between key events of adjacent joint pairings The time delays are defined as the time occurrence of an event at the proximal joint less the time occurrence of the same event at the distal joint The key events selected were the timing of joint reversal (JR), the peak instantaneous joint moment, the peak instantaneous joint power and the peak joint angular velocity during the concentric phase (MV) A negative value indicates that the event occurred in the proximal joint prior to the distal joint Measures of inter-subject and mean values of intra-subject variability are presented The timing of peak angular velocity was least variable, while the timing of peak joint moment was most variable

Table 4 15 Mean timing of joint pairings for key events and measures of inter-subject and intra-subject variability

Variable	Group Mean	Group SD	Group CV	Individual Mean SD	Individual Mean CV
knee-ankle JR (s)	0 01	0 10	9 0	0 04	1 0
hip-knee JR (s)	-0 03	0 04	-1 2	0 02	-0 2
knee-ankle Peak moment (s)	-0 03	0 12	-3 9	0 09	-8 5
hip-knee Peak moment (s)	-0 07	0 13	-1 8	0 08	0 7
knee-ankle Peak power (s)	-0 03	0 02	-0 7	0 01	-0 3
hip-knee Peak power (s)	-0 07	0 04	-0 6	0 03	-1 2
knee-ankle MV (s)	-0 02	0 01	-0 4	0 01	-0 4
hip-knee MV (s)	-0 03	0 01	-0 4	0 01	-0 3

Note JR Joint reversal
MV Peak angular velocity of the joint
knee-ankle time delay from event occurring at the knee to event occurring at the ankle
hip-knee time delay from event occurring at the hip to event occurring at the knee

A proximal-to-distal sequence was observed on average for all individuals for both the sequencing of peak angular velocity and peak joint power However, the order of sequencing was not so distinctive and consistent for the initiation of joint extension (JR) The group on average extended the hip before the ankle, and the ankle joint began to extend before the knee However, at an individual level variation in this pattern was present Nine individuals exhibited a proximal-to-distal sequence on average in all three joints, two exhibited a distal-to-proximal in all three joints, while seven did not have a proximal-to-distal or a distal-to-proximal sequential pattern but a combination (5 individuals H-A-K, 1 individual K-H-A and 1 individual A-H-K)

No significant correlation with jump height was observed for any of the temporal joint pairing at a group level (G m and G b) At an individual level a number of correlations between temporal joint pairings and jump height were observed but were predominately limited to only one or two individuals One individual (subject 10) exhibited a significant correlation between jump height and the time delay between JR of the knee and the ankle joint (r = 0 53) and the timing between the hip and the knee joint (r = - 0 83) with delays of 0 003s and -0 026s, respectively suggesting jumps of greater height also had longer delays (a minus value in delay indicates the proximal joint extended before the distal joint) Another individual (subject 11) exhibited a positive correlation between jump height and the time delay between JR of the hip joint and JR of the knee joint (r =0 54), which occurred with an average delay of 0 127s

Correlations between jump height and the delay between peak moments of adjacent joints were only significant for one individual (subject 14), the delay between the knee and the ankle peak moments (r = 0 84) and between the hip and the knee joints (r = -0 71) occurred with average delays of -0 253s and 0 223s, suggesting jumps of greater height had shorter delays

The delay between the peak power of the hip joint and the knee joint was negatively correlated with jump height (subject 18 r = -0 712) for one individual and positive for another (subject 16 r = 0 490), with average delays of -0 115s and -0 089s, respectively suggest a longer delay for subject 18 and shorter for subject 16 Finally, the delay between peak angular velocity of the knee and the ankle joint was negatively correlated with jump height (subject 9 r = -0 546) for one individual occurring with an average delay of -0 013s While the delay between peak angular velocity of the hip joint and that of the knee joint was negatively correlated for three individuals with average delays of -0 039s, -0 029s and -0 059s All correlations suggested jumps of greater height also had longer delays

4 3 Rate of force development and CMJ performance

Table 4 16 below details the mean RFD over the intervals A, B, C, D1, D2, E, F, G, H1 and H2 (Figure 3 4), and the rate of power development over the first 60ms of the concentric phase, for the ankle, knee and hip joints, and the whole body Measures of inter-subject variability and mean values of intra-subject variability are presented

Table 4 16 Mean and variance values of RFD of ankle, knee and hip joint moments, and whole body vGRF

	Group			Individual	
	Mean	SD	CV	Mean SD	Mean CV
Ankle JR to TO (E)	-2 49	1 14	-45 8	0 55	-22 3
Knee JR to TO (E)	-2 43	1 22	-50 1	0 39	-15 9
Hip JR to TO (E)	-2 60	1 00	-38 4	0 32	-12 4
Whole body JR to TO (A)	-15 36	6 48	-42 2	1 68	-10 9
Ankle min to JR (F)	0 68	0 08	11 5	0 13	19 1
Knee min to JR (F)	0 59	0 10	17 4	0 13	22 0
Hip min to JR (F)	0 95	0 09	9 5	0 16	16 8
Whole body min to JR (B)	4 36	0 56	12 9	0 91	20 9
Ankle min to peak (G)	0 69	0 11	16 3	0 13	19 0
Knee min to peak (G)	0 57	0 10	18 2	0 15	25 8
Hip min to peak (G)	0 99	0 10	10 2	0 18	17 7
Whole body min to peak (C)	4 36	0 53	12 2	0 94	21 6
Ankle min to 50% (H1)	1 17	0 15	13 1	0 21	17 9
Knee min to 50% (D2)	1 14	0 20	18 0	0 23	20 3
Hip min to 50% (D2)	1 88	0 28	15 0	0 30	16 0
Whole body min to 50% (D1)	9 36	1 32	14 1	1 94	20 7
Ankle 50% to peak (H2)	0 85	0 20	23 5	0 25	29 4
Knee 50% to peak (H2)	0 66	0 21	31 9	0 33	49 4
Hip 50% to peak (H2)	1 07	0 17	16 4	0 41	37 9
Whole body 50% to peak (D2)	4 17	0 55	13 2	1 49	35 6
Ankle power in first 60ms	9 51	6 59	69 2	14 85	156 2
Knee power in first 60ms	19 88	3 96	19 9	8 26	41 6
Hip power in first 60ms	43 86	4 58	10 4	5 87	13 4

Table 4 17 indicates the significant correlations observed between jump height and the rate of force development (RFD) The RFD over the interval from JR to take-off was negatively correlated with jump height for ankle and hip joint moments, and for the whole body vGRF (ankle r = -0 53, hip r = -0 53, whole body r = -0 50) The RFD for the knee joint was correlated with jump height only when the best jump was put forward for analysis (r = -0 47) The negative correlations indicate that jumps of

greater height a more rapid decline in force (Figure 3 4, A and E) A positive correlation over the intervals B, C, D, F, G and H, suggests that a greater RFD was observed in jumps of greater height The RFD from the instance of minimum vGRF to JR was correlated with jump height for the ankle and hip joint moment and the whole body vGRF (ankle r = 0 52, hip r = 0 57, whole body r = 0 55) Similarly, correlations were observed between jump height and RFD from the instance of minimum vGRF to peak force for the ankle and hip joint moment and the whole body vGRF (ankle r = 0 51, hip r = 0 55, whole body r = 0 52) The interval between the minimum and maximum force was sub-divided into two phases, from minimum vGRF to 50% peak moment (or vGRF) and from 50% peak moment (or vGRF) to peak moment (or vGRF) Correlations with jump height were observed for all joints and whole body for only the first phase (ankle r = 0 52, knee r = 0 53, hip r = 0 66, whole body r = 0 63), while no significant correlations were observed over the second phase The only correlation at a group level between the rate of power development (RPD) and jump height was observed for the hip joint (r = 0 48)
A number of individual correlations were observed but were at best only present in six individuals in the case of minimum vGRF to peak moment for the hip, and in development of knee power over the first 60ms of the concentric phase For a number of parameters both positive and negative correlations were observed, suggesting that for some individuals a greater RFD was desired while for others it was detrimental

Table 4 17 Correlatıon (r) between jump heıght and (ı) rate of force development and (ıı) power development over selected ıntervals

	Moment or vGRF																				Power		
	JR to TO				mın to JR				mın to peak				mın to 50%				50% to peak				JR to JR+60ms		
	A	K	H	W	A	K	H	W	A	K	H	W	A	K	H	W	A	K	H	W	A	K	H
G b	-0 55	-0 47	0 47	-0 53												0 52							
G m	-0 53		-0 52	-0 50	0 52		0 57	0 55	0 51		0 55	0 52	0 52	0 53	0 66	0 63							0 48
1														0 59									
2														0 59									
3					0 80		0 82	0 61	0 78	0 63	0 77		0 74	0 72	0 77	0 62							
4																		0 69					
5																						-0 49	
6																						-0 49	
7																							0 66
8			0 53				0 57	0 62			0 57	0 64			0 59	0 61				0 55	0 58		0 64
9			0 61	-0 56																		-0 65	
10																							
11													0 56									-0 57	
12													0 56									-0 57	
13			-0 60	-0 53	0 57		0 73	0 66	0 62		0 58								0 74	0 59		0 60	
14														0 56							0 56		
15		-0 53	0 79	-0 67			0 67	0 51	0 63	0 49	0 64						0 59	0 58	0 52			0 52	0 65
16																							
17							-0 81				-0 81												
18	0 56		-0 71								0 55						-0 56		0 73		0 57	-0 58	0 86

Note A = ankle, K = knee, H = hıp, W = whole body
JR = joınt reversal
TO = take-off
mın = ınstant where vGRF was at mınım

4 4 Comparisons of kinetics between the CMJ and the DJ

The magnitude of selected kinematics and joint kinetics were compared between the CMJ and drop jumps from 30cm (DJ30) and 50cm (DJ50), to determine the suitability of DJs as a means of training to enhance CMJ performance Table 4 18 details the mean changes in the magnitude of jump height, amplitude of the BCOM, duration of the eccentric and concentric phases, peak negative and positive whole body power in the DJ (DJ30 and DJ50) compared to the CMJ Table 4 19 details the mean changes in magnitude of joint moment at JR, peak joint moment and peak joint power for the ankle, knee and hip joint in the DJ (DJ30 and DJ50) compared to the CMJ All values are given as the magnitude observed in the DJ less that observed in the CMJ (negative values indicates DJ less the CMJ) Finally, table 4 20 summaries the results from table 4 19 also indicating the parameters which were found to be significantly correlated with jump height in the CMJ as outlined in section 4 1

As can be seen from table 4 18, jump height during DJ30 did not differ significantly from the CMJ at the group level but DJ50 was on average 2cm lower than the CMJ At an individual level, nine subjects achieved a reduced jump height for the DJ30 and the DJ50, while three and two individuals achieved greater jump height during the DJ30 and DJ50, respectively The DJ30 was executed with reduced amplitude of movement of the BCOM at the group level, and for 11 of the 18 individuals There was no significant difference in amplitude of movement between DJ50 and CMJ at the group level, but reduced amplitude was evident for 10 of the 18 individuals In contrast, greater amplitude of movement was observed for three and four individuals for DJ30 and DJ50, respectively In comparison to the CMJ reduced duration on average was observed for both the eccentric and concentric phases for both drop heights at the group level of analysis No significant difference was observed between DJ30 and DJ50 for the duration of the eccentric phase but the duration of the concentric phase was on average longer in the DJ50 than the DJ30 (G m) At an individual level, no subject used an extended eccentric phase during a DJ, however, three individuals had an extended concentric phase for DJ50 The vGRF at the start of the concentric phase in the DJ did not differ to CMJ at a group level for both DJ30 and DJ50 (G m and G b) At an individual level, eight subjects had greater vGRF at the start of the concentric phase, while six experienced greater in the DJ50

Table 4 18 Differences in jump height achieved and whole body kinematics and kinetics between CMJ and DJ from 0 3m and 0 5m

	ump height (m)		Amplitude (m)		Duration Eccentric phase (s)		Duration concentric phase (s)		vGRF at start of concentric phase (N)		Peak whole body negative power (W)		Peak whole body positive power (W)	
	30	50	30	50	30	50	30	50	30	50	30	50	30	50
G b	-0 01	-0 01	-0 06*	-0 04	-0 31*	-0 32*	-0 06 *	-0 05*	0 32	-0 09	-39 89*	-72 24*○	-3 26	-3 67
G m	-0 01	-0 02*	-0 05*○	-0 04*○	-0 31*	-0 31*	-0 06*	-0 04*○	0 23	-0 05	-37 10*	-75 50*○	-3 70*	-5 00*○
1	-0 01*	0 01○	-0 16*	-0 09*○	-0 28*	-0 27*	-0 12*	-0 08*○	-0 19	0 01	-28 18*	-50 25*○	0 60	-1 76*○
2	-0 06*	-0 08*○	-0 07*	-0 07*	-0 17	-0 17*	-0 06*	-0 06*	1 63*	1 67*	-45 71*	-98 12*○	-4 98*	-6 25*
3	-0 04*	-0 04*	-0 12*	-0 13*	-0 27*	-0 27*	-0 10*	-0 11*	2 25*	2 20*	-39 17*	-88 95*○	-1 01	0 00
4	-0 02*	-0 04*○	-0 15*	-0 15*	-0 22*	-0 22*	-0 13*	-0 13*	5 06*	5 10*	-47 48*	-102 50*○	7 94*	6 61*
5	-0 05*	-0 03*	-0 00	0 00	-0 13*	-0 13*	0 01	0 02*	-3 10*	-2 51*	-24 93*	-50 52*○	-11 95*	-10 93*
6	0 00	-0 06*○	0 03*	0 07*○	-0 24*	-0 21*	0 01	0 05*○	-2 15*	-3 20*○	-40 69*	-88 88*○	-7 98*	-13 65*○
7	-0 01	-0 04*○	-0 04*	-0 01○	-0 38*	-0 36	-0 06*	-0 01○	2 86*	0 63○	-55 65*	-102 41*○	-6 92*	-9 40*○
8	0 01*	0 03*○	-0 01	0 07*○	-0 24*	-0 23*○	-0 08*	-0 04○	-3 30*	-3 11*	-12 56*	-26 75*○	-11 12*	-12 74*○
9	-0 02*	-0 04*	-0 05	-0 06	-0 73*	-0 73*	-0 08*	-0 06*○	2 48*	2 63*	-27 82*	-57 02*○	-7 70*	-6 86*
10	-0 03*	-0 04*	-0 16*	-0 15*	-0 34*	-0 32*	-0 11*	-0 11*	2 96*	3 17*	-51 37*	-56 94*	8 71*	7 37*
11	0 01	-0 02○	0 00	-0 04*○	-0 33*	-0 37*	-0 04*	-0 06*	-0 62	-0 32	-55 62*	-117 20*○	-3 62*	-4 82*
12	-0 01	-0 01	-0 04*	-0 00○	-0 18*	-0 15*○	-0 02*	0 00○	-3 15*	-3 24*	-22 30*	-43 56*○	-4 49*	-5 43*
13	0 02*	0 01○	-0 06*	-0 04*○	-0 32*	-0 26*	-0 06*	-0 02*○	-0 09	-1 19*○	-35 71*	-102 67*○	-1 36*	-3 48*○
14	0 01	-0 00	-0 07*	-0 04*○	-0 54*	-0 52*	-0 10*	-0 08*	0 91*	0 72	-26 55*	-72 76*○	-2 46	-5 07*○
15	0 06*	0 03*○	0 06*	0 07*	-0 27*	-0 24*	-0 00	0 02*○	1 96*	0 54	-35 08*	-65 80*○	-1 20*	-6 62
16	-0 01	0 00	0 02*	0 02*	-0 47*	-0 46*	0 00	0 01	-0 21	-0 58	-42 38*	-78 76*○	-5 33	-4 96*
17	-0 03*	-0 02*	-0 09*	-0 09*	-0 33*	-0 34	-0 11*	-0 12*	1 05	1 38*	-34 02*	-80 28*○	-3 84*	-3 81*
18	-0 02*	-0 01	-0 09*	-0 06*○	-0 26*	-0 31*	-0 09*	-0 05*○	-0 42	-0 92*	-36 81*	-89 66*○	-2 34*	-2 89*

Note * = differs from CMJ at α = 0 05 level of significance
○ = differs from DJ30 at α = 0 05 level of significance
-ve = CMJ > DJ

Peak whole body negative power was greater in the DJ30 than the CMJ and greater again in the DJ50 This pattern was also present at an individual level for all subjects except one (subject 10) that did not exhibit a difference between the DJ30 and the DJ50 (G m and G b) At a group level peak whole body positive power was less in the DJ30 than the CMJ and less again in the DJ50 (G m only) At an individual level lower peak whole body positive power was observed for 12 and 14 subjects for DJ30 and DJ50, respectively, while five of these exhibited a reduced power in the DJ50 than the DJ30

The use of DJ as a training intervention is primarily to provide an overload to specific elements of the neuromuscular system For DJ to be an appropriate means of overloading desired elements of the neuromuscular system, magnitudes of segmental kinetic parameters need to be greater in the DJ than those experienced during the CMJ Table 4 19 details the difference in joint moment at JR, peak joint moment and peak joint power for the ankle, knee and hip between the DJ and the CMJ (DJ - CMJ) A visual summary is provided in table 4 20

At the group level, ankle moment at JR was not found to be significantly different in the DJ compared to the CMJ However, at an individual level ankle moment was greater for seven and eight of the 18 individuals for the DJ30 and the DJ50, respectively, while it was found to be lower in a further four and five for the DJ30 and the DJ50, respectively More similarity in the results between the group and individuals analysis was observed at the knee and hip joints At the group level, knee moment at JR was greater in the DJ than the CMJ and was found to be less for the hip joint These patterns were replicated for the majority of subjects at an individual level (knee DJ30 = 15, DJ50 = 12, hip DJ30 = 13, DJ50 = 15) No significant difference was observed for peak ankle moment between the DJ and the CMJ at the group level However, at an individual level greater peak ankle moments were observed for both DJ30 and DJ50 than during CMJ in four individuals Peak knee moments were found to be greater during the DJ at the group level of analysis and the pattern was replicated at the individual level in 12 of the 18 individuals Peak hip moment was found to be less in the DJ than the CMJ at both the group level, and for 17 of the 18 individuals for both the DJ30 and the DJ50

Table 4 19 Differences in joint kinetics between CMJ and DJ from 0 3m and 0 5m

	Ankle moment at JR (Nm)		Knee moment at JR (Nm)		Hip moment at JR (Nm)		Peak ankle moment (Nm)		Peak knee moment (Nm)		Peak hip moment (Nm)		Peak ankle power (W)		Peak knee power (W)		Peak hip power (W)	
	30	50	30	50	30	50	30	50	30	50	30	50	30	50	30	50	30	50
G b	0 05	0 05	0 96*	0 67*○	-1 19*	1 06*	-0 18	-0 12	0 79*	0 65	-1 51*	-1 14*	4 61*	-5 28*	11 08*	10 63*	-6 95*	-6 00*
G m	0 22	0 12	1 03*	0 83*○	-1 17*	-1 03*	-0 08	0 13	0 87*	0 86*	-1 38*	-1 17*	3 34*	-4 26*○	9 44*	9 47*	-6 24*	-5 72*
1	0 57*	0 43*	0 76*	0 53*	-1 32*	-0 52*○	0 72*	0 49*	1 08*	0 88*	-1 19*	-0 35*○	1 70	-1 04○	7 89*	7 68*	-5 71*	4 01*
2	0 42*	0 44*	2 22*	2 20*	-2 16*	-1 95*	0 16	0 20	1 93*	2 03*	-3 46*	-3 45*	-4 06*	-3 92*	13 86*	15 77*	-8 82*	9 48*
3	0 86*	1 07*	1 64*	2 35*	-1 09*	1 28*	0 63*	0 82*	1 76*	2 13*	-1 04*	-1 21*	-1 54	-1 11	9 67*	13 27*	6 00*	-8 18*
4	2 95*	2 97*	3 28*	3 26*	-2 62*	-2 41*	2 01*	2 05*	2 89*	2 73*	-3 62*	3 61*	5 56*	5 70*	16 16*	18 07*	-14 25*	14 91*
5	-0 92*	-0 96*	0 01	-0 06	-1 63*	1 42*	-0 94*	0 99*	0 12	0 13	-1 53*	-1 31*	-11 02*	-11 53*	9 05*	11 31*○	-5 26*○	-4 50*
6	-0 33	-0 97*○	0 35*	0 09○	-0 61*	0 68*	-0 52*	-0 90*○	0 15	-0 02	-0 79*	-0 90*	8 66*	-11 53*○	8 00*	4 99*○	-2 28*	-3 21*
7	0 48*	0 01○	1 07*	0 49*○	0 33	0 30	-0 04	-0 32*○	0 34	0 09	-0 29	-0 38*	5 65*	-6 18*	7 24*	4 84*○	-3 01*	-2 57*
8	-0 57*	-0 70*	0 20	0 06	2 86*	2 36*○	-0 76*	0 95*	-0 85	-0 98	-2 64*	-2 14*○	-9 05	-11 21	-0 53	-0 81	-11 04*	-9 76*
9	0 34	0 08	1 40*	1 71*	0 15	0 24	0 05	-0 12	0 63*	0 96*	-0 52*	-0 49*	2 51*	-3 02*	4 30*	3 66*	-3 04*	-2 76*
10	1 36*	1 63*	2 50*	2 02*	2 57*○	-1 97*	0 98*	1 41*	1 67*	2 14*	-3 46*	-2 00*○	5 08*	4 27*	14 32*	18 59*	10 69*	-8 17*○
11	-0 02	-0 12	1 11*	0 95*	-0 39	-0 56*	0 20	-0 19	0 36*	0 57*	-0 66*	-0 65*	-2 59	-3 01	9 37*	7 62*	-7 32*	-7 41*
12	-0 80*	-1 05*	0 08	-0 31	-1 42*	-1 07*	-0 56*	-0 65*	0 12	0 26	-1 40*	-1 07*	-3 88*	-4 38*	9 79*	8 19*	-5 05*	-2 65*○
13	0 18	-0 20	0 98*	0 46*○	-1 47*	-1 44*	-0 06	-0 31*○	0 92*	0 45*○	-1 40*	-1 35*	-1 30	-3 86*○	11 77*	11 92*	-6 16*	-5 70*
14	0 32	0 49*	0 55*	0 29	-0 30	0 10○	-0 41*	-0 42*	0 47*	0 24*	-0 79*	-0 33*○	-3 07*	-3 99*	9 74*	6 44*○	-4 16*	-2 20*○
15	0 73*	0 94*	2 14*	1 47*○	-0 67*	-0 80*	-0 51*	-0 30*	1 90*	1 40*○	-0 70*	0 65*	-6 89*	-6 74*	10 68*	7 88*○	-5 49*	-4 13*○
16	-0 33*	-0 57*	0 58*	0 38*	-0 13	0 40*	-0 31*	-0 50*○	0 04	0 08	-0 48*	0 69*	-4 56*	-5 39*	3 88*	5 70*○	-5 59*	-5 02*
17	0 21	0 36*	1 28*	1 26*	-0 91*	-0 37○	-0 21	-0 06	1 18*	1 37*	-0 61*	-0 13○	-6 17*	-6 07*	11 97*	10 49*	-7 24*	-5 95*
18	0 16	-0 07	0 58*	0 19○	-1 47*	0 94*○	0 12	-0 11	0 82*	0 57*○	-1 51*	1 07*○	-1 20	-3 42*○	10 01*	9 26*	-4 98*	-3 98*

Note * = differs from CMJ at α = 0 05 level of significance
○ = differs from DJ30 at α = 0 05 level of significance

At a group level of analysis both peak ankle joint power and peak hip joint power were found to be lower in both the DJ30 and the DJ50 compared to the CMJ This was evident at the individual level for all subjects for hip power and, 11 and 12 of the 18 subjects, respectively, for the DJ30 and the DJ50 However, for two individuals (subject 4 and 10) peak ankle joint power was greater in the DJ than the CMJ Increases in the magnitude of peak knee joint power were also observed in the DJ compared to the CMJ at both the group level and at an individual level for 17 of the 18 subjects Differences between peak knee joint power in the DJ30 and the DJ50 were evident in six individuals but not at a group level However, four exhibited a greater peak knee power in the DJ50, while another two exhibited greater magnitude in the DJ30 Differences between the DJ30 and the DJ50 were also observed for the peak ankle power at both the group level (G m only) and at the individual level for four subjects, all with greater magnitude in the DJ30 No difference was observed in peak hip joint power at a group level but five subjects exhibited greater magnitude in the DJ30 at the individual level

While a number of kinetic variables have been seen to be overloaded in the DJ (DJ30 and DJ50) in comparison to the CMJ, both at a group and individual level, in order for DJs to produce a positive enhancement in the CMJ performance, the variables overloaded must be limiting factors of CMJ performance For detail of the identification of performance limiting factors, we refer the reader to the section 4 1 Table 4 20 details the significant differences between the CMJ and the DJ, indicates the kinetic parameters were been found to be correlated with jump performance

Of the two of individuals that exhibited positive correlations between ankle moment at JR and jump height, only one was overloaded in the DJ and in the case of hip moment at JR none of the four While four individuals that were positively correlation between peak ankle moment and jump height, only one showed overloaded in the DJ compared to the CMJ None of individuals positively correlated between jump height and peak hip moment, peak ankle power or peak hip power, exhibited an overload of these parameters in the DJ compared to the CMJ However, subject 14 who was positively correlated between jump height and peak knee joint power had a greater magnitude of peak knee joint power in the DJ50 compared to the CMJ, and greater again in the DJ30

Table 4 20 Kinetic parameters overloaded in the DJ compared to the CMJ, with parameters significantly correlated with jump height in CMJ indicated

	vGRFstart concentric phase (N)	Ankle moment at JR (Nm)	Knee moment at JR (Nm)	Hip moment at JR (Nm)	Peak ankle moment (Nm)	Peak knee moment (Nm)	Peak hip moment (Nm)	Peak negative power (W)	Peak positive power (W)	Peak ankle power (W)	Peak knee power (W)	Peak pow (W
G b	ns	ns ●	<50<30	30 50	ns ●	< 30	30 50	<30 <50		30 50	< 30, 50	30
G m	ns ●	ns ●	<50<30	30 50	ns ●	< 30, 50	30 50	<30 <50 ●	30 50 ●	30 50	< 30, 50	30
1	ns	<30, 50	<30, 50	50 30	<30, 50 ●	<30, 50	50 50	<30 <50	50	ns	<30, 50	50
2	<30, 50	<30, 50 ●	<30, 50	50 50	ns ●	<30, 50	30	<30 <50	30 50	30	<30,50	30
3	<30, 50	<30, 50	< 30, 50	30 50	<30, 50	<30, 50	30 50 ●	<30 <50	ns	ns	<30, 50	30
4	<30, 50	<30, 50	<30, 50	30 50	<30, 50	<30, 50	50 50	<30 <50	<30, 50	<30, 50	<30, 50 ○	0
5	30 50	30 50 ○	ns	30 50	30 50	ns	30 50	<30 <50	50	30	<30, 50	30
6	30 50	30 50	< 30	30 50	30 50	ns	30 70	<30 <50	50 50 ●	30 50 ●	<50<30	30
7	<50<30	<30	<50 <30	n	50	ns	50 ●	<30 <50	50 50 ●	30 50	<50<30	30
8	50 ●	30 50	ns	50 30	30 50	ns	50 50	<30 <50	30 50	30 50	ns	30
9	<30, 50	ns	<30, 50	ns ●	ns	<30<50 ○	30 50	<30 <50	ns ●	30 50 ●	<30, 50	30
10	<30, 50	<30, 50	< 30, 50	30 50	<30, 50	<30, 50	50 30	<30 <50	<30, 50 ●	<30, 50	<30, 50	50
11	ns	ns	<30, 50	50	ns ●	<30, 50	30 50	<30 <50	30 50 ●	ns	<30, 50	30
12	<30, 50	30 50	ns	30 50	30 50	ns	30 50	<30 <50	30 50 ●	30 50 ●	<30, 50	50
13	30 ●	ns ●	<50<30	30 50 ●	50	< 50 <30	30 50 ●	<30 <50	30 50	50	<30, 50	30
14	<30	<50	<30	ns	30 50 ●	<30, 50	50 30	<30 <50	30 50 ●	30 50 ●	<50<30 ●	50
15	<30	<30, 50	<50<30	30 50 ●	30 50	<50 <30	30 50 ●	<30 <50	30 ●	30 50 ●	<50<30	50
16	ns	30 50	<50, 30	30	50 ●	ns	30 50	<30 <50	50 ●	30 50	<30<50	30
17	<50	<50	<30, 50	50	ns	<30, 50	30	<30 <50	30 50	30 50	<30, 50	30
18	50	ns	<30	50 30 ●	ns ○	<50 <30 ○	50 30 ●	<30 <50	30 50	50	<30, 50	30

Note < = magnitude of parameter greater in the DJ than the CMJ

● = positive correlation between parameter and CMJ jump height at $\alpha = 0$ 05 level of significance

○ = negative correlation between parameter and CMJ jump height at $\alpha = 0$ 05 level of significance

Discussion

The predominate methodology that has been utilised in biomechanical analysis, is to compare differences between individuals, referred to as group analysis This group approach assumes that the movement strategy for all individuals is the same However, not every athlete has the same neuromuscular capacity (e g individual joint power, rate of power production and joint dominance), anthropometrics (e g limb length and relative mass) and muscle morphology (e g percentage muscle fibre type), and diverse movement strategies have been observed It may be more appropriate to make inferences about an individual's movement strategy by treating each individual as their own experiment group, examining differences between repetitions of an individual's own performance, referred to as individual analysis The results of the two approaches will be discussed, firstly, in relation to what biomechanical factors correlate with countermovement jump (CMJ) performance and secondly, the difference in the kinetics between the CMJ and the drop jump (DJ)

The section will start with a discussion of the differences between the magnitude of inter-subject and intra-subject variability The factors found to be correlated with jump height at a group level will be compared with the factors found at an individual level Possible reasons will be outlined for the discrepancies between the two forms of analysis Questions that need to be addressed over the selection of which biomechanical parameter to be trained with a view to enhancing CMJ performance will be outlined Finally, the results comparing the neuromuscular overload in the DJ, over that of the CMJ, will be discussed in relation to the potential use of the DJ as a training intervention to enhance CMJ performance

5 1 Inter-subject verses Intra-subject variance

As expected, variability was evident both between the 18 subjects (inter-subject variability) and within the 15 jumps of each individual (intra-subject variability) Across all parameters there was greater inter-subject variability than intra-subject variability In many cases inter-subject variability was two to three times that of intra-subject, which was similar to the differences found by Aragon-Vargus and Gross (1997a, 1997b) for vertical jump kinematics and kinetics The inter-subject variability reflects not only the varying strategies employed, but also differences due to neuromuscular capacity, anthropometrics and muscle morphology, while intra-subject variability reflects changes only in the jump strategy used

Whole body kinematics and kinetics were generally less variable than the corresponding joint measures, both at the inter-subject and intra-subject level This can be partly attributed to the compensating ability of the multilinked human system, allowing whole body kinetics to be maintained in the face of changes at one joint being offset by changes at another (Dowling and Vamos, 1993) Kinetic measures were found to be in general more variable than kinematic measures These findings have also been observed in other studies of vertical jumping (Aragon-Vargas and Gross, 1997a, Rodacki et al, 2001, van Soest et al, 1985) and other movements such as walking and running (DeVita and Skelly, 1990, Dufek et al, 1995) Again this is likely to be a reflection of maintaining an overall kinematic movement strategy, which can be produced through a variety of joint kinetic strategies

There was greater variability in parameters in the eccentric phase than the concentric phase Since one of the requirements for maximizing jump height is to maximise mechanical energy at take-off (Bobbert and van Ingen Schenau, 1988), this results in a relatively consistent configuration of the body at take-off, with all the joints of the lower extremities being nearly fully extended (Bobbert and Van Soest, 2001) The use of a greater variability in the eccentric phase and at the transition between the phases may be due to variations having a smaller effect on jump performance, or that the performer has less capacity to integrate information from the eccentric phase than the concentric phase to optimise jump performance

5 2 Group analysis

A statistical analysis at the group level, where differences between individuals have been examined, has predominantly been employed in identifying factors that relate to performance success In the biomechanical literature the selection of a representative value for an individual has predominately taken two forms the mean magnitude of values observed and the value corresponding to the best performance Table 4 12 outlines the mechanical parameters that were correlated with jump height at the group level, using the best performance (G b) and the mean values (G m) In general the biomechanical factors revealed when using the best performance were also revealed when using the mean values However, the converse was not true, just over half the biomechanical factors revealed using the mean values were also revealed using the values from the best jump When the values from the best performance were used, the magnitude of all biomechanical parameters from that jump are regressed against the jump height achieved, not just those parameters that were responsible for achieving that height As a number of diverse biomechanical strategies may be selected to maximise jump height, the use of the values from the best jump may obscure the identification of factors relating to jump height at the group level The presence of individual strategies still persists when mean values are used, but as it is the "typical" characteristics that are put forward for analysis, it may prove a more robust method

In the present study, the group approach identified a number of parameters that were significantly correlated with jump height (table 4 15), peak negative vertical velocity of the BCOM (r= 0 60), peak positive power (r= 0 56), peak negative power (r= 0 58), positive work done during the concentric phase (r= 0 48), vGRF at the start of the concentric phase (r= 0 47) and the duration of the eccentric phase (r= -0 47)

Taking the eccentric phase first, the related factors of a high peak vertical velocity and power, and a short duration, may be beneficial to improving jump height Only two studies appear to have directly examined the relationship between mechanical parameters of the eccentric phase and jump performance Dowling and Vamos (1993) found both peak vertical velocity (r= 0 29) and power (r = 0 30) to be correlated with jump height but the strength of the relationships were less than those reported in the present study While Aragon-Vargas and Gross (1997a) did not explicitly examine the negative velocity of the BCOM, they did find peak negative impulse to correlate with jump height (p<0 02) These findings are also consistent with the observation that improvements in jump height in the CMJ over that of the squat jump (SJ) are greater with faster and shorter eccentric phases (Bosco et al, 1981, Cavagna, 1977, Komi, 2000)

Vertical ground reaction force (vGRF) at the start of the concentric phase was found to be correlated with jump height (r= 0 47) This is inconsistent with the findings of Dowling and Vamos (1993) who found no significant correlation Bobbert et al (1996) examined improvements in jump height in the CMJ over the SJ using mathematical modelling based on actual jump data They attributed the enhancement to greater force at the start of the concentric phase in the CMJ, allowing larger joint moments during the first part of joint extension At the whole body level both peak positive power and positive work done were found to correlate with jump height Other researchers have also reported peak power to correlate with jump height (Aragon-Vargas and Gross, 1997a, Dowling and Vamos, 1993, Harman et al, 1990) In these studies correlations (r) of 0 68, 0 93 and 0 86, respectively, were reported, compared to 0 76 within the present study One possible reason for the lower correlation found by Aragon-Vargas and Gross (1997a) is they did not normalise for body weight When power was not normalised for body weight within the present study, the correlation fell to 0 56 The strong association between jump height and peak power indicates that high forces need to be accompanied by rapid execution This would suggest that training should aim to develop strength specifically at high velocities (Dowling and Vamos, 1993) In contrast to the present study, previous studies have found peak vGRF to correlate significantly with jump height (Dowling and Vamos, 1993, Harman et al, 1990) The amount of positive work done in the concentric phase was positively correlated with jump height in the present study No previous studies appear to have examined how a change in the amount of work done was relates to jump performance While Aragon-Vargas and Gross (1997a) did not explicitly examine work done, they found average power and phase duration were positively related to jump height in many prediction models As work done is the product of average power and duration, a relationship between jump height and work done may have existed

No relationship was found between the duration of the concentric phase and jump height, supporting previous findings by Dowling and Vamos (1993) However, Aragon-Vargas and Gross (1997a) included concentric phase duration as part of a prediction model for take-off velocity, suggesting it was negatively related to jump height at a group level

While knowledge of the relationships between jump height and jump mechanics at the whole body level is important, more specific information can be achieved by examining the relationship at the joint level At the joint level a number of parameters correlated significantly with jump height peak angular velocity of the hip during the eccentric phase (r= 0 64), ankle positive work done (r= 0 58), peak ankle power (r=0 58), peak knee power (r= 0 52), peak ankle moment (r= 0 51), ankle moment at joint reversal (r= 0 49) and coupling time at the hip (r= -0 48)

In the present study the joint that exhibited the greatest number of significant correlations with jump height was the ankle joint In contrast, Aragon-Vargas and Gross (1997a) found hip kinetic parameters (peak hip power and peak hip moment) exhibited the strongest correlations, with peak knee power only included within models already containing hip kinetic parameters None of their models included ankle kinetic measures However, at an individual level many of their models contain peak ankle power and peak ankle moment, but hip kinetic parameters still dominated their models (Aragon-Vargas and Gross, 1997b) Variation between individuals in the relative contribution of each joint to total work done has been found (see table 4 11) (Hubley and Wells, 1983) It is possible that the joints showing significant correlations with jump height may be specific to each sample group of individuals

5 3 Comparison between group and individual level

If comparable results are observed for both the group analysis and the individual analysis, this would suggest that all individuals perform alike and the group approach may be suitable for identifying performance strategies for all individuals However, it was found that no parameter that was significantly correlated with jump height at the group level was also significantly correlated for all subjects at an individual level The two variables with the greatest degree of correspondence between the two forms of analysis were total positive work done and peak positive power, correlating at an individual level in 11 and 9 of the 18 individuals, respectively Aragon-Vargas and Gross (1997b) similarly found peak whole body power to be a significant predictor of jump height for all eight individuals they examined While they did not examine work done per se, average power and duration of the concentric phase were also significant for all individuals

For the eccentric and the transition phases, few subjects exhibited significant correlations at an individual level for the whole body parameters that were found to correlate significantly at the group level Only four subjects exhibited a correlation at an individual level for peak velocity and eccentric phase duration, while no individuals had correlations for peak negative power Additionally, in contrast to the concentric phase, where consistencies in the direction of the relationships were observed, directly opposing relationships were observed in the eccentric phase Three individuals exhibited a negative correlation between jump height and the duration of the eccentric phase, matching the results of the group analysis, while a single subject (subject 4) exhibited a positive relationship A negative relationship suggests a fast and forceful downwards movement of the body in the eccentric phase would benefit jump performance, enabling a high velocity of stretch of the muscles and greater force at the start of the concentric phase, which have been previously reported to enhance jump height (Bosco et al, 1979, Bosco et al, 1982a, Komi, 2000) The positive relationship observed for subject four is in contradiction to this However, the relationship can be explained by an interaction of some of the parameters In additional to the correlation with phase duration, the amplitude of movement of the BCOM was also correlated with jump height (r= 0 69) for this subject To accommodate the greater range of motion over which to develop force, extended eccentric and concentric phases were therefore employed This suggests the presence of two different strategies, one involving a rapid and shallow movement which utilises the SSC, and the other which involves greater movement amplitude, providing a greater distance over which to apply force

The results of the group and individual analysis appear to be less comparable at the joint level than at the whole body level (table 4 12), with at best eight individuals exhibiting a correlation for a parameter that was also revealed at the group level (i e ankle work done) Additionally, there were a greater number of parameters exhibiting opposite relationships with jump height between individuals (e g ankle moment at JR) Differences were more evident in the eccentric and transition phases than the concentric phase Aragon-Vargas and Gross (1997a and 1997b) also found a reduced comparability between the two forms of analysis at the joint level However, the biomechanical parameter they found to exhibit the strongest correlation with jump height at the group level was still evident in six of the eight subjects at the individual level, and was also the single best predictor of jump height for one individual (subject W) (Aragon-Vargas and Gross, 1997a) The reduced comparability between the results of the group and individual analyses at the joint level is possibly a reflection of the compensatory ability of the multi-segmental nature of the human body, allowing the same whole body kinetic pattern to be achieved using numerous combinations of joint kinetic strategies (Hubley and Wells, 1983)

In the present study, several parameters were also found to be significantly correlated with jump height for a number of subjects at an individual level, but were not significantly correlated at a group level The amplitude of movement of the BCOM, the vertical difference of the BCOM from standing to take-off, the duration of the concentric phase (table 4 8), peak hip moment, peak hip power and work done at the hip (table 4 10), were all found to be correlated with jump height in at least five individuals, but not at the group level Aragon-Vargas and Gross (1997a and 1997b) found this same pattern for the amplitude of movement of the BCOM, the vertical difference of the BCOM from standing to take-off and the duration of the concentric phase However, while Aragon-Vargas and Gross (1997b) also found peak hip power and peak hip moment to be related to jump height at an individual level, correlations were also observed at the group level (Aragon-Vargas and Gross, 1997a)

At the group level, the hip joint was found on average to contribute the most to total work done, but this was not observed in all subjects The relative contribution that each joint made to the total work done was not found to be correlated with jump height, for any joints at a group level However, a number of significant correlations were observed at the individual level (table 4 11), suggesting while no ideal pattern may exist for all individuals, an optimum pattern particular to an individual may still exist In addition, both positive and negative correlations were observed between jump height and work done at various joints

5 4 Coordination

At a group level the hip extends on average 0 03 seconds before the knee, with the ankle extending 0 01 seconds before the knee However, when the average sequence for an individual was calculated, this hip-ankle-knee sequence was only exhibited by five subjects Nine individuals had a proximal to distal sequence and two subjects had a distal to proximal sequence Two subjects had some other combination of joint extension This mixed pattern of joint reversal (JR) has been previously observed (Aragon-Vargus & Gross, 1997a, Jensen et al, 1991, Rodacki et al, 2001, Rodacki et al, 2002) Rodacki et al (2001) found that three of the twelve subjects in their study extended the ankle before the knee, and 21 of the 52 subjects in the study by Aragon-Vargus & Gross (1997a) extended the joints in a hip-ankle-knee pattern A shorter delay between the JR of the hip and the knee was observed in the present study (knee 0 03s after the hip), compared to other studies (Jensen et al, 1994, Rodacki et al, 2001, Rodacki et al, 2002)

Peak joint moments followed a proximal to distal sequence, with the peak hip moment occurring on average 0 07 seconds before the knee, followed by the peak ankle moment on average 0 03 seconds later A proximal to distal sequence was only observed in ten individuals However, a proximal to distal sequence of peak joint power was found in all individuals, which is consistent with the findings of Rodacki et al (2001) and Rodacki et al (2002) The delay is also comparable to the 0 023 seconds and 0 046 seconds found by Rodacki et al (2001) and Rodacki et al (2002), respectively However, while Rodacki et al (2002) found a delay between peak knee power and peak hip power of 0 088 seconds, which is comparable to the average delay of 0 07 seconds in this study, Rodacki et al (2001) found a slightly greater delay of 0 187 seconds

A proximal to distal sequence of peak joint angular velocity was also found at the group level and in all individuals, in the present study, which is consistent with the findings of Jensen et al (1994) However, a proximal to distal sequence was not observed by Rodacki et al (2001), where peak hip angular velocity occurred 0 01 seconds before the ankle and knee, nor was it observed by Rodacki et al (2002), where hip and ankle peak velocities occurred simultaneously, followed by the knee

0 012 seconds later While small delays were evident in these studies (see table 2 19), marginally greater delays occurred in the present study

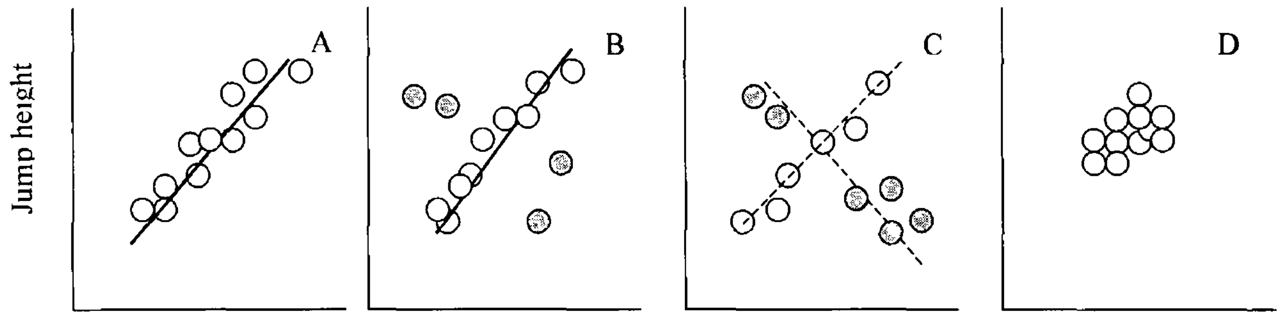
None of the time delays were correlated with jump height at a group level Two possible explanations for this are, firstly, that the sequencing is already optimised as the skill is well learnt Secondly, that while an optimal timing may exist for an individual, these optimal sequences differ between individuals, perhaps due to differences in neuromuscular capacity and anthropometrics

While no significant relationship was observed at a group level between jump height and the delay in JR between adjacent joints, significant correlations were observed for two individuals One individual had a positive correlation between jump height and the delay between knee JR and ankle JR (r=0 529), and a negative correlation with the delay between the hip JR and the knee JR (r= -0 832) Another individual had a positive correlation between jump height and the delay between hip JR and knee JR (r=0 537) It is unknown how much the delay should be altered as correlations only report the sign/direction of a change, but not the magnitude of change It is possible the relationship may change once a critical delay is achieved This is one of the limitations of the correlation method

5 5 Inter-subject analysis verses Intra-subject analysis

The predominant approach to identifying performance driving or performance limiting biomechanical factors is to undertake a group based analysis By comparing individuals, it is assumed that a significant relationship reflects a more optimum movement strategy Similarly, if no relationship is present for a given variable, it is assumed that the magnitude of the variable does not affect performance This group based approach presumes that a single, 'abstract' optimal movement strategy exists and it can be applied to all individuals This would be true if everyone was physically identical However, individuals differ in their neuromuscular capacity (e g individual joint power, rate of power production and joint dominance) their anthropometrics (e g limb length and relative mass) and their muscle morphology (e g percentage muscle fibre type) Therefore, no single optimal movement strategy may be present In consequence, the negative effect of a group based analysis may be that it identifies an 'optimal' movement strategy that is in fact detrimental to the performance of an individual In addition, a movement strategy that would benefit many individuals may not be observed in a group analysis, simply due to a contrasting strategy from a few individuals masking its occurrence Given that the present study clearly found differences in results using a group based in comparison to an individual based correlation analysis, it is important to at least examine the theoretic implications of a causal relationship being revealed when the biomechanical parameters are systematically altered and the relationship with jump height follows the same pattern as observed in the correlation analysis

The identification of a casual relationship may not always provide a definitive answer as to whether the parameter should or should not be trained to enhance jump performance When a mechanical parameter is related to jump height at the group level (Figure 5 1a), it is suggested that all individuals should train this parameter However, this may not always be the case, a situation may arise where a strategy present in a majority of individuals (e g 80%) dominates the group analysis, suggesting all individuals (Figure 5 1b) should train this biomechanical factor However, the training of this biomechanical factor may not be beneficial to the minority (e g 20%) of the other individuals in the group, or may in fact be detrimental to their performance Similarly, when no relationship is present at a group level it does not necessarily imply that this parameter is not related to jump performance for some individuals Firstly, a case where contrasting strategies between individuals mask each others detection with correlation analysis may exist (Figure 5 1c) For example, some individuals may increase power at the hip joint while others find it more fruitful to increase the power of the ankle joint, resulting in jumps of greater height with both low and high peak ankle power, potentially obscuring the strategies at the group level Secondly, if little variability in the mechanical parameter is present at the group level, an underlying relationship may not be revealed by correlation analysis (Figure 5 1d) This low variance may be due to an optimum existing and be widely employed, resulting in the mean for each individual being centred on a common point A selection of a more heterogeneous sample group may increase the variability and the underlying relationship may be revealed



Mechanical Parameter

Figure 5 1 Possible relationships between jump height and a mechanical parameter

If a relationship between the magnitude of a biomechanical parameter and jump height is observed at an individual level, this suggests that the strategy of altering this factor could increase jump height, indicating the benefits to training this factor Conversely, if no relationship is found for an individual, it may suggest that this factor should not be trained However, an underlying relationship with jump height may still exist, and may not have been revealed in the correlation analysis purely due to insufficient intra-subject variability The low intra-subject variability may be caused by the current and limited level in neuromuscular capacity imposing a constraint or the individual may have settled into a none optimum, invariant movement pattern simply because they have never attempted other movement strategies

While it is possible that the same kinematic and kinetic strategy would be revealed using both a group and an intra-subject analysis, results from the present study indicate little commonality (table 4 12) For example, peak eccentric power correlated significantly at a group level, but no individuals exhibited a significant correlation When comparing the results of a group and an individual analysis a number of outcomes are possible, table 5 1 represents the six possible scenarios

Table 5 1 Representation of possible scenarios between group and individual analysis

	GROUP CORRELATION		
		YES	NO
INDIVIDUAL CORRELATION	ALL	1	2
	SOME	3	4
	NONE	5	6

At one end of the spectrum, scenario 1 refers to when a parameter is significantly correlated with jump height at both the group level and for all subjects at an individual level, explaining both why some individuals jump higher and why some jumps of an individual are higher than other jumps At the other end of the spectrum of possible responses, scenario 6 refers to where no correlation with jump height at either the group or the individual level is present Neither of these scenarios occurred for any of the variables in the present study Scenario 5 is where a correlation is present at a group level, but not at an individual level for any subjects, this is the case within the present study for peak eccentric whole body power Since differences were observed between individuals, this may reflect differences in neuromuscular capacities Scenario 2 is the case where the parameter is correlated for all subjects at an individual level, but not at a group level This suggests all subjects should train this factor Two possible explanations may be put forward to why no correlation was observed at the group level Firstly, the magnitude of the mechanical factor may indeed be important in jump height achievement, but the individuals' means were centred on a common point, possibly an optimum level, thus reducing group variability Secondly, the level of the mechanical factor is important, but individuals have different optimums The differing optimums may be related to the differences in physical characteristics of the individuals, or due to differing strategies being employed by individuals For example, one individual may use a large range of movement and small eccentric loading, while another may use a small range of movement and large eccentric loading, but both individuals may produce the same jump height

In the present study the majority of parameters fall under scenario 3 and 4, where not every individual performed the same Scenario 3 presents a situation where a parameter is correlated with jump height at both the group level and at the individual level for a number of subjects This was the case for ankle positive work done in the present study Scenario 4 is where some individuals exhibit a correlation, but no correlation was observed at the group level, as was the case in the present study for peak hip power

The results of the group analysis may suggest that the better performers utilised a certain strategy but it may not be true to say that, if all individuals utilised that strategy they would increase performance, as the strategy may not be suitable for them given their physical characteristics While differing strategies may be the result of individual perceptions of performance outcome, it is the physical characteristics of an individual that may play the greatest role in the selection and success of a given strategy It is possible that these physical characteristics may predispose individuals to certain strategies and therefore different optimums Due to differences in limb length corresponding position of the BCOM at the start of the concentric phase between individuals may require different knee angles (Alexander, 1995), in turn the optimum knee angle may depend on the current neuromuscular capacity (Thorstenssen et al, 1976) and muscle morphology (Bosco et al, 1982a) of the individual

Bosco et al (1982a) found that for individuals with a high percentage of fast twitch muscles, jumps of smaller knee amplitude resulted in a greater enhancement of kinetics than larger amplitudes in the concentric phase of a CMJ over that of a SJ However, for individuals with greater number of slow twitch fibres jumps of larger amplitude allowed more time for force to build up and resulted in a greater percentage relative enhancement of kinetics than jumps of small amplitude Therefore for a group of individuals with diverse muscle morphology and stature, potentially jumps of differing amplitude of movement will result in jumps of greater height for these individuals, as highlighted by the differing relationships observed for amplitude of movement of the BCOM (table 4 6) and duration of the eccentric phase (table 4 2)

5 6 Questions arising over the selection of which parameters to alter

Four questions should be considered when deciding whether a biomechanical parameter is worth training to enhance jump height Firstly, how strong is the relationship between the biomechanical factors related to differences in jump height? Secondly, how much will a change in the biomechanical factor increase jump height? Thirdly, by how much can the biomechanical factor be trained? Fourthly, what is the magnitude of biomechanical factor for the individual relative to the group mean? An indication of the strength of the relationship between the biomechanical parameter and jump height can be revealed by the correlation coefficient (r), the larger correlation coefficient (r) the more of the variability in jump height can be explained by the variability in the biomechanical parameter If a strong and significantly relationship is revealed through correlation, the extent to which a change in the mechanical parameter causes a change in jump height must be examined Information regarding the possible extent of the change is available from the slope of the bivariate relationship The steeper the slope, the more jump height seen to increases when a change in the biomechanical parameter occurs As can be observed in figure 5 1, greater jump height is achieved in 'scenario c' compared to 'scenario a', and in 'scenario d' compared to scenario b', for comparable changes in the biomechanical parameter However, as can also be observed, a greater increase in jump height is achieved in 'd' than in 'a', with a corresponding slope, by virtue of a greater range over which the biomechanical parameter is altered An indication of the potential range over which the biomechanical parameter can be altered may be revealed by the sample variance, both intra-subject and inter-subject From the four scenarios outlined in figure 5 1, it is evident that a large slope is not enough to achieve a large increase in jump height, but the correct combination of slope and variation in the biomechanical parameter is required Finally, the magnitude of the biomechanical factor for the individual, relative to the group, must be considered If an individual already produces a high magnitude in comparison to the group, there may be less scope for improvement in comparison to an individual demonstrating a lower magnitude This is evident in a number of training studies, which have shown that the neuromuscular training response is largest in those who have not previously training (Plisk, 2001)

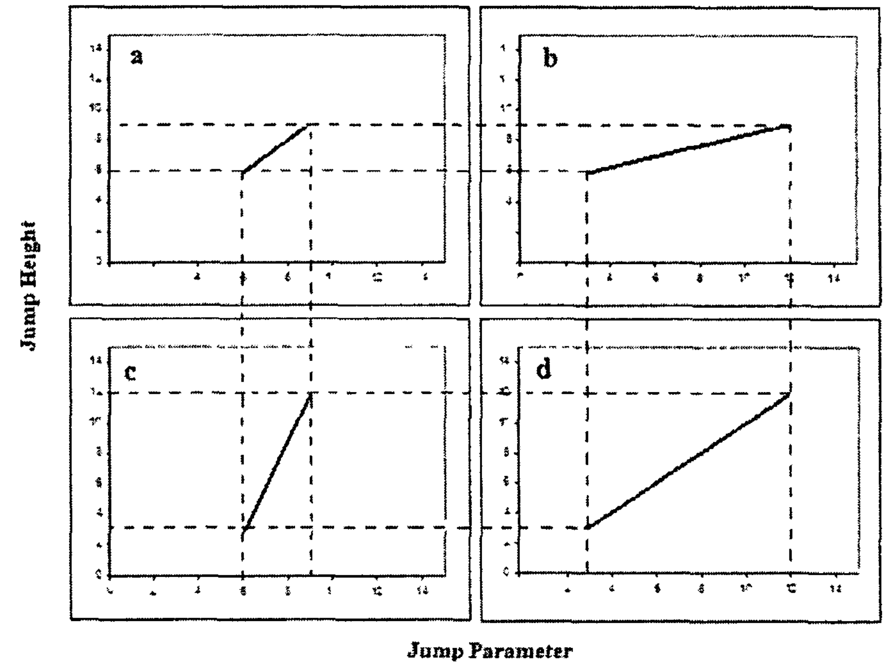


Figure 5 2 Interaction of variability and slope of relationship between jump height (y axis) and a mechanical jump parameter (x axis)

Examples of the interaction of slope and variance are illustrated in table 4 13 The mean magnitude, amount of variance (standard deviation [SD] and coefficient of variability [CV]) and slope, are reported for four jump parameters peak ankle moment, hip negative work done, peak hip power and knee angle at JR In relation to figure 5 1, peak ankle moment represents 'scenario a', peak hip power 'scenario b', knee angle at JR 'scenario c', and hip negative work done 'scenario d' A comparison of negative work done at the hip revealed that for subjects 5 and 6, a greater slope of the relationship with jump height than that for subjects 3, 4, 14 and 18 Furthermore, the variance and mean magnitude is lower For these two individuals, it appears that training this parameter may provide a greater increase in jump height than training another parameter This is true, providing the amount of negative work done can be increased further In respect to the group mean, this appears possible In the case of subject 16, for peak hip power, both the variance and the slope of the relationship with jump height are low In this case, it may not be prudent to spend time training this already high magnitude, and training should centre on a different variable

5 7 The use of drop jumps as a means of training the CMJ

The drop jump (DJ) has been used as a training method to enhance countermovement jump (CMJ) performance, with differing levels of success For example, Blatter and Noble (1979) found that CMJ height increased on average 2 1cm after a training program involving DJs, while Matavuji et al (2001) observed a 5 6cm increase after a comparable training program However, Brown et al (1986) found no significant increase after a more extensive training program For DJs to be a successful method of enhancing CMJ performance they must (i) have a similar movement pattern (in relation to the muscle groups used, the coordination pattern, the joint range of motion (ROM), the velocity of contraction and the muscle action), (ii) provide an overload of the neuromuscular system, and (iii) train those factors that are related to CMJ height The DJ clearly provides a close qualitative match with the CMJ in relation to the movement pattern employed The extent to which the kinetics are overloaded in the DJ, and the ability of the DJ to overload the specific jump kinetic parameters that relate to differences in performance success in the CMJ are discussed below In addition, the implications of the differences in findings at a group and individual level are addressed

Peak whole body negative power was found to be significantly enhanced with increases in eccentric loading, with the greatest magnitudes produced in the DJ50, followed by the DJ30 and then CMJ These findings were consistent at both the group level and the individual level, for all but one subject This result is hardly surprising since when landing in the DJ the BCOM has a higher negative vertical velocity than that experienced in the CMJ, and increases with drop height

All three knee joint kinetic parameters examined (knee moment at JR, peak knee moment, peak knee power) were greater in the DJ compared to the CMJ, both at the group level and for the majority of individuals This is consistent with the findings of Bobbert et al (1986a) at a group level for the bounce drop jump (BDJ) and Bobbert et al (1987a) for both the counter drop jump (CDJ) and the bounce drop jump (BDJ) Only one difference was evident at the group level between DJ30 and DJ50, with a significantly greater knee joint moment at JR produced from DJ30 than DJ50 At an individual level, drop height had a significant effect on only a small number of subjects knee moment at JR (n = 2), peak knee moment (n = 2) and peak knee power (n = 6) It appears that while DJs provide a suitable means of overloading the knee joint kinetics, the effect of drop height may be minimal In contrast to the knee joint, hip joint kinetics (hip moment at JR, peak hip moment, peak hip power) were lower in the DJ than the CMJ at a group level, and for the majority of subjects at the individual analysis level In contrast, Bobbert et al (1986a) found no difference in hip joint kinetics between the DJ and the CMJ While Bobbert et al (1987a) also found no difference in peak hip power, they did find lower hip moments at JR for the BDJ and lower peak hip moments for both the CDJ and the BDJ

At a group level, the vGRF at the start of the concentric phase, ankle moment at joint reversal and peak ankle moment, were not different in the DJs in comparison to the CMJ, while peak whole body power and peak ankle power were significantly lower in the DJ than the CMJ The lack of increase in these parameters is consistent with the results of Bobbert et al (1986a) for DJs employing comparable movement amplitudes as the CMJ (CDJ) However, Bobbert et al (1986a, 1987a) observed increased magnitudes in DJs that utilised a significantly reduce movement amplitude, but increased peak ankle power was only observed by Bobbert et al (1987a) for DJs with a greater reduction in movement amplitude (BDJ = 24cm reduction) In the present study, for these same kinetic measures, a number of individuals exhibited greater magnitudes in the DJ in comparison to the CMJ Interestingly, these subjects tended to use a smaller amplitude of movement, which in light of the findings by Bobbert et al (1986a, 1987a) may explain these findings For example, nine subjects had an increase in ankle joint moment at JR in the DJ compared to the CMJ, with a further five exhibiting a reduction Of the nine individuals that displayed an increase in ankle moment at JR, eight utilised a DJ technique with a smaller amplitude of movement, while four of the five with a reduced ankle moment at JR utilised a larger movement amplitude than that of the CMJ Similarly, only four individuals had a greater peak ankle moment in the DJ than the CMJ and all of these individuals employed 10cm less amplitude of movement in the DJ than the CMJ (the only four individuals in the study with such a reduction) Finally, two individuals (subject 4 and subject 10) who had greater peak positive whole body and ankle power in the DJ compared to the CMJ, utilised a substantial reduction in movement amplitude (16cm)

A possible explanation for the effect of a smaller amplitude of movement enhancing the magnitude of overload in the DJ over the CMJ for selected kinetic variables, may be that when a small amplitude is used the BCOM must decelerate quicker This may result in the time that elapses between the peak stretch of the muscles and the start of the concentric muscle contraction being kept short Bosco et al (1982a) found that a higher velocity of stretch in the eccentric phase and a higher vGRF at the start of the concentric phase occurred in jumps with less knee range of motion A short "coupling time" and a fast stretch have been found to enhance the kinetics on the concentric phase (Bosco et al, 1981, Cavagna et al, 1968)

The only differences in jump kinetics at a group level between the two drop heights were a lower whole body peak power, ankle peak power and peak knee moment at JR in DJ50 than DJ30 A number of differences were observed at the individual level, the majority suggesting lower kinetics in the DJ50 than the DJ30 It appears that increasing the amount of negative work done by altering the drop height did not appear to be a successful method of overloading kinetics

5 8 The suitability of drop jump as a means of training the CMJ

While a number of kinetic variables have been seen to be overloaded in the DJ (DJ30 and DJ50) in comparison to the CMJ, both at a group and individual level, in order for DJs to produce a positive enhancement in the CMJ performance, the variables overloaded must be limiting factors of CMJ performance Examination of table 4 17 clearly shows that at a group level, of the five kinetic parameters correlated with jump height, only peak negative power was overloaded This suggests that DJs provide a suitable means of training peak negative power to enhance CMJ height, however, the use of DJ to train the other kinetic parameters does not seem worthwhile At an individual level, only three subjects experienced an overload in a kinetic parameter that was correlated with the CMJ height for them It appears that DJs would only provide a suitable means of training the CMJ for these individual However, DJ training may provide a suitable training stimulus for the CMJ for more individuals When a biomechanical parameter is correlated with jump height at a group level, it reflects not only differences in strategies employed but also differences in the neuromuscular capacities between individuals Therefore, a significant correlation at a group level, may suggest all individuals should train that kinetic factor (e g peak ankle moment) While overload was not observed at a group level, it was for some individuals and the possibility exist that alteration of the DJ technique of the other individuals may induce an overload Examination of an individual in isolation may help in explaining why a lack of response to DJ training However, comparison of an individuals overload pattern in the DJ to that of other individuals may help to guide future training interventions using the DJ to provide a training stimulus to enhance CMJ height

5 9 Conclusion

A number of biomechanical factors were found to be significantly correlated with CMJ jump height at a group level Those factors that were correlated with jump height at the group level however, were not always correlated at the individual level, and visa versa A number of diverse movement strategies were evident at the individual level, either involving different biomechanical factors or the same factors but with the opposite relationship with jump height The existence of opposing strategies may mask the identification of a key strategy at the group level, but also potentially identify a strategy as being optimal when in fact it may be detrimental to the performance of some individuals Similar discrepancies between the group and individual analysis approach were observed for shock attenuation in landing (Dufek et al, 1995, Lees, 1981) and running (Dufek et al, 1995, Lees and Bouracier, 1994) and for jump height achievement in the CMJ (Aragon-Vargas and Gross, 1997a, 1997b) Discrepancies between the results of a group and an individual analysis were also evident in the extent to which kinetic parameters were overloaded in the DJ compared to the CMJ Knee joint kinetics were significantly overloaded in the DJ at both a group level and for the majority of individuals While no significant overload was apparent for ankle kinetics at a group level, overload was achieved by a number of individuals when a reduced amplitude of movement was used At the hip joint, no overload in joint kinetics was apparent at either a group or individual level Increasing drop height did not appear to provide an greater overload of joint kinetics It appears that considerable differences were evident between the group and the individual analyses for both identification of the performance determining factors of the CMJ and the extent to which the DJ overloaded these factors This may partially explain the contrasting findings from a number of training studies (Blatter and Noble, 1979, Brown et al, 1986, Matavuji et al, 2001) examining the use of DJs to enhance CMJ performance

A considerable amount of important information may be lost regarding individual performance strategies when a group analysis is employed However, the use of solely individual analyses would not reveal any performance a factor relating to differing neuromuscular capacities between subjects, and a case for a group analysis to be used to supplement an individual analysis therefore exists This clearly requires further research involving training studies to examine which of the two approaches (group and individual analyses), or what combination of the two, is most appropriate

5 10 Future research

1) Once a causal relationship has been established between a biomechanical parameter and jump height Examine whether individual analysis provides important biomechanical information that can be used to optimise training interventions (more so than a group analysis) This can be realised through a number of study designs

a) Train a large number of individuals and examine if an increase in jump height is greater in those individuals who a relationship exists between jump height and the trained (overloaded) joint kinetic variable

b) Train two groups, one group of individuals who all exhibit a relationship between jump height and the joint kinetic variable being overloaded and one group with no relationship, and examine if there is a difference in the response to training between the two groups

2) Examine a wider range of drop heights and skill levels to determine if that changes the extent to which an individual's joint kinetics are overloaded

3) Examine the extent to which exercises to overload the neuromuscular system, other than the DJ, overload the joint kinetics produced during the CMJ, and to whether the results differ between a group analysis and an individual subject analysis

If drop height or skill level (research area 2) and exercise (research area 3) change to varying degrees, the extent to which joint kinetics are overloaded at an individual subject level, then the results should drive further research into identifying optimal training interventions (research area 1)

4) Examine for other sporting actions, other than the vertical CMJ (e g long jump, high jump), if those correlated with performance success differ at the group and individual level of analysis

References

Alexander, R, McN (1995) Leg design and jumping technique for humans, other vertebrates and insects *Phil Trans Royal Soc London* **347**, 235-248

Anderson, F C and Pandy M G (1993) Storage and utilization of elastic strain energy during jumping *Journal of Biomechanics* **26**(12), 1413-1427

Aragon-Vargas L F and Gross M M (1997) Kinesiological Factors in vertical jump performance differences among individuals *Journal of applied Biomechanics* **13,** 24-44

Aragon-Vargas L F and Gross M M (1997) Kinesiological factors in vertical jump performance differences within individuals *Journal of applied biomechanics* **13,** 45-65

Asmussen, E and Bonde-Petersen, F (1974) Storage of elastic energy in skeletal muscle in man *Acta physiol Scand* **91**, 385-392

Bangerter, B L (1964) Contributive components in the vertical jump *The Research quarterly* **39**(3) 433-437

Bates, B T (1996) Single subject methodology an alternative approach *Med Sci Sport Exerc* **28**(5), 631-638

Bedi, J F , Cresswell A G Engel, T J , and Nicol, S M (1987) Increase in jumping height associated with maximal effort vertical depth jumps *Research Quarterly* **58**(1), 11-15

Bernstein, N (1967) *Coordination and regulation of movement* (1st Ed) Pergamon Publications, NY

Blattner, S and Noble, L (1979) Relative effect of isokinetic and plyometric training on vertical jumping performance *Research Quarterly* **50**, 583-588

Bobbert M F (1990) Drop jumping as a training method for jumping ability *Sports medicine* **9**(1) 7-22

Bobbert, M F , Mackay, M , Schinkelshoek, D , Huijing, P A and van Ingen Schenau (1986a) Biomechanical analysis of drop and countermovement jumps *Eur J Appl Physiol Occup Physiol* **54**(6), 566-573

Bobbert M F Huijing P A and Van Ingen Schenau G (1986b) A Model of the human triceps surae muscle-tendon complex applied to jumping *J Biomechanics* **19**(11), 887-898

Bobbert M F Huijing P A and Van Ingen Schenua G J (1986c) An estimation of power output and work done by the human triceps surae muscle-tendon complex in jumping *J Biomechanics* **19**, 899-906

Bobbert, M F , Gerritsen, K G , Litjens, M C and van Soest, A J (1996) Why is countermovement jump height greater than squat jump height? *Medicine, Science, Sport and Exercise* **28**(11), 1402-1412

Bobbert M F, van Soest A J (2001) Why do people jump the way they do? Exercise and Sport Science Review **29**(3), 95-102

Bobbert, M F , Huijing, P A and van Ingen Schenan, G (1987a) Drop jump I *Med Sci Sport Exerc* **19**, 332-338

Bobbert, M F , Huijing, P A and van Ingen Schenan, G (1987a) Drop jump II *Med Sci Sport Exerc* **19** 339-346

Bobbert, M F and van Ingen Scheneau, G J (1988) Coordination on vertical jumping *J Biomechanics* **21**, 249-262

Bobbert, M F & van Soest, A J (1994) Effect on muscle strengthening on vertical jump height A simulation study *Med Sci Sport Exerc* **26**, 1012-1020

Bosco, C and Komi, P V (1979) Mechanical characteristics and fiber composition of human leg extensor muscles *Eur J Appl Physiol* **41**, 275-284

Bosco, C , Komi, P V and Ito, A (1981) Prestrech potentiation of human skeletal muscle during ballistic movement *Acta Physiol Scand* **111**, 135-140

Bosco, C , Tihanyi, J , Komi, P V , Fekete, G and Apor, P (1982a) Store and recoil of elastic energy in slow and fast types of human sketal muscles *Acta Physiol Scand* **116**, 343-349

Bosco, C Viitasalo, J T Komi, P V and Luthanen, P (1982b) Combined effect of elastic energy and myoelectrical potentiation during stretch-shortening cycle exercise *Acta Physiol Scand* **114** 557-565

Brown M E , Mayhew J L and Boleach L W (1986) Effect of plyometric training on vertical jump performance in high school basketball players *J Sport med and phys fitness* **26**, 1-4

Bozelli, G , Cappozzo, A and Papa, E (1999) Inter- and intra-individual variability of ground reaction forces during sit-to-stand with principal component analysis *Med Eng Phys* **21**(4), 235-40

Burgess-Limerick, R , Neal, R J and Abernethy, B (1992) Against relative timing invariance in movement kinematics *Q J Exp Psychol* **44**(4), 705-22

Button, C , MacLeod, M , Sanders, R and Coleman, S (2003) Examining movement variability in the basketball free-throw action at different skill levels *Res Q Exerc Sport* **74**(3), 257-69

Cavaghan P R & Kram, R (1989) Stride length in distance running velocity, body dimensions, and added mass effect *Med Sci Sport Exerc* **21**(4), 467-479

Cavagna, G A , Saibene, F P and Margaria, R (1965) Effect of negative work on the amount of positive work performed by an isolated muscle *J Appl Physiol* **20**(1), 157-158

Cavagna, G A , Dusman, B and Margaria, R (1967) Positive work done by a previously stretched muscle *Journal of applied physiology* **24**(1), 21-32

Cavagna, G A (1977) Storage and utilization of elastic energy in skeletal muscle *Ex Sp Sci Rev* **5**, 89-104

Clark, J E , Phillips, S J and Petersen, R (1989) Developmental Stability in jumping *Development Psychology* **25**(6) 929-935

Clutch, D , Wilton, M , McGown, C and Bryce, G R (1983) The effect of Depth Jumps and weight training on leg strength and vertical jump *Res Quart* **54**, 5-10

Craib M Caruso C Clifton R Burleson C Mitchell V Morgan D (1994) Daily Variation in step length of trained male runners *Int J Sports Med* **15**, 80-83

DeVita, P and Bates, B T (1988) Intraday reliability of ground reaction force data *Human movement science* 7(1), 73-85

DeVita, P and Skelly, W T (1990) Intrasubject variability of lower extremity joint moments of force during the stance phase of running *Human movement science* **9**(2), 99-115

Diedrick, F J and Warren, W H (1995) Why Change Gait? Dynamics of the Walk-Run Transition *Journal of Experimental Psychology Human Perception and Performance* **21**(1), 183-202

Dowling, JL & Vamos, L (1993) Identification of Kinetic and temporal factors related to vertical jump performance *Journal of applied Biomechanics* 9, 95-100

Driss T Wandewalle H Monod H (1998) Maximal power and force-velocity relationships during cycling and cranking exercises in volleyball players *J Sports med Phy Fitness* **38**, 286-93

Dufek, J D , Bates, B T , Stergiou, N and James, C R (1995) Interactive effect between group and single-subject response patterns *Human movement science* **14**, 301-323

Dufek, J D and Bates, B T (1990) The evaluation and prediction of impact forces during landings *Medicine and Science in Sport and Exercise* **22**, 370-377

Dufek, J D and Bates, B T (1991) Dynamic performance assessment of selected sports shoes on impact forces *Medicine and Science in Sport and Exercise* **23**, 1062-1067

Eisenman, P A (1978) The influence of initial strength levels on responses to vertical jump training *J Sports Med* **18**(3), 277-282

Fry, A , C and Newton, R , U (2002) A brief history of strength training and basic principles and concepts IN *Strength training for sport* Eds Kraemer, W J and Hakkinen, K pp 1-19 Blackwell science, Oxford

Fukashiro S and Komi P V (1987) Joint moment and mechanical power flow of the lower limb during vertical jump *Int J Sports Med* **8**(Suppl 1), 15-21

Gehri D J Ricard M D Kleiner D M Kirkendall D T (1998) A comparison of plyometric training techniques for improving vertical jump ability and energy production *Journal of Strength and conditioning association* **12**(2), 85-89

Gentner, D R (1987) Timing of skilled motor performance Tests of the proportional duration model *Psychological review* **94**(2), 255-276

Gregoire, L , Veeger, P A , Huijing, P A and van Ingen Schenau, G J (1984) Role of Mono- and Biarticular muscles in explosive movements *Int J Sports Med* **5**, 301-305

Hakkinen, K (2002) Training-specific characteristics of neuromuscular performance IN *Strength training for sport* Eds Kraemer, W , J and Hakkinen, K pp 20-36 Blackwell science, Oxford

Hakkinen, K (1991) Force production characteristics of leg extensor, trunk flexor and extensor muscles in male and female basketball players *J Sports Med Phys Fitness* **31**(3), 325-331

Hair, J F (1987) *Multivariate data analysis with readings* 2nd ed New York Macmillan

Hamill, J , Bates, B T and Knutzen, K M (1984) Ground reaction force symmetry during walking and running Research quarterly for exercise and sport **55**(3), 289-293

Hamill, J , van Emmerik, R E , Heiderscheit, B C and Li, L (1999) A dynamical system approach to lower extremity running injuries *Clinical biomechanics* **14**, 297-308

Hamill, J and McNiven, S L (1990) Reliability of selected ground reaction force parameters during walking *Human movement science* **9**(2), 117-131

Harman, E A , Rosenstein, M T , Frykman, P N , Rosenstein, R M (1990) The effects of arms and countermovement on vertical jumping *Med Sci Sport Exerc* **22**(6), 825-33

Hay, J G , Dapena, J , Wilson, B D , Andrews, J & Woodward, G (1978) An analysis of joint contributions to performance of a gross motor skill IN Asmussen, E and Jorgensen, K (Eds) *Biomechanics VI-B* Baltimore University Park Press pp 64-70

Hay, J G (1995) The case for a jump-dominated technique in the triple jump *Track Coach* **132**, 4214-4219

Heiderscheit, B C (2002) Variability of Stride characteristics and joint coordination among individuals with unilateral patellofemoral pain *J applied biomechanics* **18**, 110-121

Heiderscheit, B C (2000) Movement variability as a clinical measures for locomotion *J applied biomechanics* **16(4)**, 418-427

Hopkins, W G & Wolfinger, R D (1998) Estimating "individual differences" in the response to an experimental treatment *Med Sci, Sport Exerc* **30**, S125

Hubley, C L , Wells, R P A work-energy approach to determine individual joint contributions to vertical jump performance *Eur J Appl Physiol Occup Physiol* **50**(2), 247-54

Hudson, J L (1986) Coordination of Segments on vertical jump *Med Sci Sport Exerc* **18**, 242-251

Hunter, J P and Marshall, R N (2002) Effects of power and flexibility training on vertical jump technique *Med Sci Sport Exerc* **34**(3), 478-486

Izquierdo, M , Aguado, X , Gonzalez, R , Lopez, J L and Hakkinen, K (1999) Maximal and explosive force production capacity and balance performance in men of different ages *Eur J Appl Physiol* **79**, 260-267

Jacobs, R and van Ingen Schenau, G J (1992) Control of an external force in leg extensions in humans *J Physiol* **457**, 611-626

Jaric, S , Ristanovic, D and Corcos, D M (1987) The relationship between muscle kinetic parameters and kinematic variables in a complex movement *Eur J Appl Physiol Occup Physiol* **59**(5), 370-6

Jensen J L Phillips S J (1991) Variation on vertical on the vertical jump Individual adaptations to changing task demands *Journal of Motor Behaviour* **23**(1), 63-74

Jensen J L Phillips S J and Clark J E (1994) For young jumpers, differences are in the movement's control, not its coordination *Research quarterly for exercise and sport* **65**(3), 258-268

Johnson M D and Buckley J G (2001) Muscle power patterns in the mid-acceleration phase of sprinting *Journal of Sports Sciences* **19**, 263-272

Kerin, D (2002) Achieving strength gains specific to the demands of jumping events *Track Coach* **160**, 5103-5110

Kollias, I, Hatzitaki, V, Papaiakovou, G and Giatsis, G (2001) Using principal components analysis to identify individual differences in vertical jump performance *Research Quarterly for exercise and sport* **72**(1), 63-67

Komi, P V (2000) Stretch-shortening cycle a powerful model to study normal and fatigued muscle *J Biomech* **33**(10), 1197-206

Komi, P V and Vitasalo, J (1979) Signal characteristics of EMG at different levels of muscle tension *Acta Physiologica Scandinavica* **96**, 267-276

Kreamer, W J & Newton, R A (1994) Training for improved vertical jump *Gatorade Sports science Institute* 7(6)

Latash, M L, Scholz, J P and Schoner, G (2002) Motor control strategies revealed in the structure of motor variability *Exerc Sports Sci Rev* **30**(1), 26-31

Lees A and Fahmi E (1994) Optimal drop heights for plyometric training *Ergomomics* **37**(1), 141-148

Lees, A Bouracier, J (1994) The longitudinal variability of ground reaction forces in experienced and inexperienced runners *Ergonomics* **37**, 197-206

Linthorne, N P (2001) Analysis of standing vertical jumps using a force platform *American Journal of Physics* **69**(11), 1198-1204

Luhtanen P, Komi PV (1978) Segmental contribution to forces in vertical jump Eur J Appl Physiol Occup Physiol **38**(3), 181-188

Maraj, B K Elliott, D, Lee, T D and Pollock, B J (1993) Variance and invariance in Expert and Novice Triple Jumpers *Res Q Exerc Sport* **64**(4), 404-412

Marcora, S and Miller M K (2000) The effect of knee angle on the external validity of isometric measures of lower body neuromuscular function *J Sports Sci* **18**(5), 313-9

Matavulj, D Kukolj, M, Ugarkovic, D Tihanyi, J and Jaric, S (2001) Effects of plyometric training on jumping performance in junior basketball players *J Sports med phys fitness* **41**, 159-64

Miller, D I and East, D J (1976) Kinematic and kinetic correlates of vertical jumping in women IN *Biomechanics V* (Ed) Komi, P V University Park Pass, Baltimore

Moran, K (1998) A biomechanical evaluation of the effect of the stretch shortening cycle in unconstrained and experimentally constrained vertical jumps PhD thesis, unpublished

Montgomery, D C (1991) *Design and analysis of experiments* (3rd Ed) John Wiley and sons, New York

Mullineaux, D R , Bartlett, R M and Bennett, S (2001) Research design and statistics in biomechanics and motor control *Journal of Sports Science* **19**, 739-760

Nagano A, Ishige Y and Fukashiro, S (1998) Comparison of new approaches to estimate mechanical output of individual joints in vertical jumps *J Biomechanics* **31**(10), 951-555

Nagano, A and Gerritsen, G M (2001) Effect of neuromuscular strength training on vertical jumping performance- A computer simulation study *Journal of Applied Biomechanics* **17**, 113-128

Newell, K M and Slifkin, A B (1998) The nature of Movement Variability IN Piek, J P (Ed) *Motor Behaviour and Human Skill* Human Kinetics, Champaign, IL pp143-160

Newton, R D (1998) Expression and development of maximum muscle power PhD thesis, unpublished

Orr, D B (1994) *Fundamentals of applied statistics and surveys* Chapman and Hall, New York

Paasuke, M Ereline J and Gapeyeva, H (2001) Knee extension strength and vertical jumping performance in Nordic combined athletes *J Sports Med Phys Fitness* **41**(3), 354-361

Pandy, M G , Zajac, F E , Sim, E and Levine, W S (1990) An optimal control model for maximum-height human jumping *J Biomechanics* **23**(12), 1185-98

Pandy M G , Zajac F E (1991) Optimal muscular coordination strategies for jumping J Biomech **24**(1), 1-10

Plisk, S (2001) Muscular strength and stamina IN *High-performance sports conditioning* (Ed) Foran, B Human Kinetics, Champaign, IL pp 63-82

Podolsky, A , Kaufman, K D , Cahalan, T D , Sergfei, P T , Aleshinsky, Y and Chao, E Y S The relationship of strength and jump height in figure skaters *The American Journal of Sports Medicine* **18**(4) 400-405

Putnam, C A (1991) A segment interaction analysis of proximal-to-distal sequential segment motion patterns *Med Sci Sport Exerc* **23**(1), 130-144

Ravn, S , Voigt, M , Simonsen, E B , Alkjaer, T , Bojsen-Møller, F and Klausen K (1999) Choice of jumping strategy in two standard jumps, squat and countermovement jump - effect of training background or inherited preference? *Scand J Med Sci Sports* **9**(4), 201-8

Robertson DG, Fleming D (1987) Kinetics of standing broad and vertical jumping *Can J Sport Sci* **12**(1), 19-23

Robertson D G E and Fleming D (1987) Kinetics of Standing broad and vertical jumping *J Sport Science* **12**(1), 19-23

Rodacki A L Fowler N E and Bennett S J (2000) Multi-segment coordination a fatigue effects *Med Sci Sport Exerc* **33**(7), 1157-1167

Rodacki A L Fowler N E and Bennett S J (2001) Vertical jump coordination fatigue effects *Med Sci Sport Exerc* **34**(1), 105-117

Rodano, R and Roberto, S (2002) Stability of selected lower limb joint kinetic parameters during vertical jump *J applied biomechanics* **18**, 83-89

Sale, D (1992) Neural adaptations to strength training IN Komi, P (Ed) *Strength and Power in Sport* Blackwell Scientific London

Saliba, L and Hrysomallis, C (2001) Isokinetic strength related to jumping but not kicking performance of Australian footballers *J Sci Med in Sport* 4(3), 336-347

Sayers, S P, Harackiewicz, D V, Harman, E A, Frykman, P N and Rosenstein, M T (1999) Cross-validation of three jump power equations *Med Sci Sport Exerc* **31**(4), 572-577

Schache, A G , Bennell, K L , Blanch, P D & Wrigley, T V (1999) The coordinated movement of the lumbo-pelvic-hip complex during running a literature review *Gait and Posture* **10**(1), 30-47

Schieb D A (1986) Kinematic accommodation of novice treadmill runners *Res Q Exer Sport* **57**, 1-7

Schmidt, R A (1985) A Schema Theory of Discrete Motor Skill Learning *Psychological Review* **82**(4), 225-260

Siff, M C (1998) *Supertraining* (5th Ed) Supertraining Institute,

Stergiou, N , Jensen J L , Bates B T , Scholten, S D and Tzetzis, G (2001) A dynamical system investigation of lower extremity coordination during running over obstacles *Clinical Biomechanics* **16** , 213-221

Stigler, S M , (1986) *The history of statistics the measurement of uncertainty before 1900* Belknap press of Harvard University Press, Cambridge, Mass

Thorstensson, A , Grimby, G and Karlsson, J (1976) Force-velocity relations and fiber composition in human knee extensor muscles *J Appl Physiol* **40**(1), 12-6

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**, 181-187

Toumi, H , Thiery C Maitre S Martin A Vanneuville G Poumarat G (2001) Training effects of amortization phase with eccentric/concentric variations –The vertical jump Int J Sports Med **22**, 605-610

Turvey M T (1990) Coordination *American Psychologist* **45**(8), 938-953

Ugarkovic, D , Matavuly, D , Kukolj, M and Jaric, S (2002) Standard anthropometric, body composition, and strength variables as predictors of jumping performance in elite junior athletes *Journal of Strength and Conditioning Research* **16**(2), 227-230

Van Ingen Schenau, G J , Bobbert, P A , Huijing, P A and Woittiez, R D (1985) The instantaneous torque-angular velocity relation in plantar flexion during jumping *Med Sci Sport Exerc* 17(4), 422-426

Van Ingen Schenau, G J , Bobbert, P A , and Rozendal, R H (1987) The unique action of bi-articular muscles in complex movements *J Anat* **155**, 1-5

Van Soest, A J , Roebroeck, M E , Bobbert, M F , Huijing, P A and Van Schenau, G J (1985) A comparison of one-legged and two-legged countermovement jumps *Med Sci Sport Exerc* 17(6), 635-639

Van Soest, A J , Schwab, A L , Bobbert, M A and Van Ingen Schenau, G J (1993) The influence of the biarticularity of the gastrocnemius muscle on vertical-jumping achievement *J Biomechanics* **26**(1), 1-8

Voigt, M , Simonsen, E B , Dyhre-Poulsen, P and Klausen, K (1995) Mechanical and muscular factors influencing the performance in maximal vertical jumping after different prestretch loads *J Biomechanics* **28**(3), 293-307

Walshe, A D , Wilson G J and Ettema, J C (1998) Stretch-shorten cycle compared with isometric preload contributions to enhanced muscular performance *J Appl Physiol* **84**(1), 97-106

Wilson, G J , Lyttle, A D , Ostrowski, K J and Murphy, A J (1995) Assessing dynamamic performance A comparison of rate of force development tests *J Strength and Conditioning Research* 9(3), 176-181

Winter, D A (1990) *Biomechanics and motor control of human movement* (2nd Ed) Wiley, New York

Wisloff, U Castagna, C Helgerud, J Hones, R and Hoff, J (2004) Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players *J Sports med* **38**, 285-288

Young, W , Wilson, G and Byrne C (1999a) Relationship between strength qualities and performance in standing and run-up vertical jumps *J Sports Med Phys fitness* **39**, 285-293

Young W B Wilson G J Byrne C (1999b) A comparison of drop jump training methods effects on leg extensor strength qualities and jumping performance *Int J Sports med* **20**, 295-303

Young, W (1995) Laboratory strength assessment of athletes *New studies in athletics* **10**(1), 89-96

Zajac, F E, Neptune, R R and Kautz S A (2002) Biomechanics and muscle coordination of human walking Part 1 Introduction to concepts, power transfer, dynamics and simulations *Gait and Posture* **16**, 215-232

Zajac F E (1993) Muscle coordination of movement a perspective *J Biomechanics* **26**(1), 109-124

Appendix

INVESTIGATION OF WITHIN-SUBJECT VARIABILITY AS A MEAN TO IDENTIFY PERFORMANCE INHANCEMENT INTERVENTIONS

Investigator Gary Park

Supervisor Kieren Moran

1 I have been requested by Gary Park to participate in a research study part of his Master degree program The testing will occur at the department of Sports Science and Health, Dublin City University

2 The purpose of the study is to assess the effect of a tailored training program to enhance vertical jump performance based on the individual's strengths and weaknesses

3 *Experimental protocol*

I will be required to perform 20 to 30 maximal effort vertical jumps in the laboratory Lightweight reflexive marks will be placed at various locations on the body with adhesive tape Film data will be recorded by motion analysis system and all jumps will be recorded on a force platform Subjects will be placed into groups based on jumping style I will then undertake an eight-week training program, 3 times per week At the completion of the training program, I will return to the laboratory and the initial test session will be repeated

4 I understand that there are foreseeable risks to my safety if I agree to participate in the study The major risk involved is an accident while jumping

5 I understand that there are no feasible alternative procedures available for this study

6 I understand that any data or video footage collected from my involvement in the study will only be available to the investigator or project supervisor and will be kept within their custody

7 I understand that the results of the study may be published but that my name or identity will not be revealed

8 I have been informed that any questions I have concerning the study or my participation in it, before or after my consent, will be answered

9 I understand that I am under no obligation and am free to withdraw consent and to discontinue participation in the study at any time without penalty or loss of benefit to myself

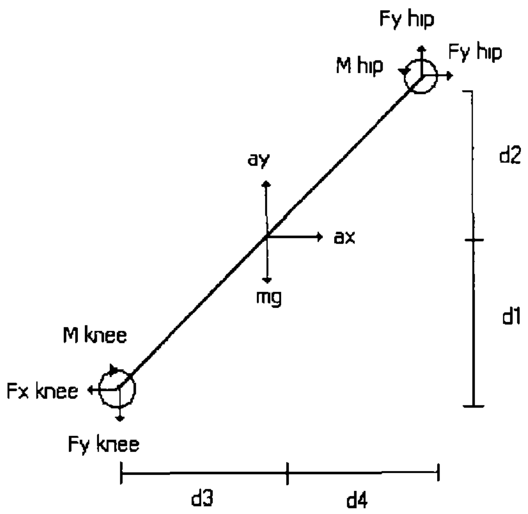
10 I have read and understand the above information The nature, demands, risks and benefits of the study have been explained to me In signing this consent form, I am not waiving any legal claims, rights or remedies A copy of this consent form will be given to me on request

Subject's name (block capitals)

Subject's signature **Date**

11 I certify that I have explained to the above individual the nature and purpose, the potential benefit and possible risks associated with participation in the study I have answered any questions that have been raised, and have witnessed the above signature

Investigator's signature **Date**



$\Sigma F_x = ma_x$

$F_x hip - F_x knee = ma_x$

$F_x hip = ma_x + F_x knee$

$\Sigma F_y = ma_y$

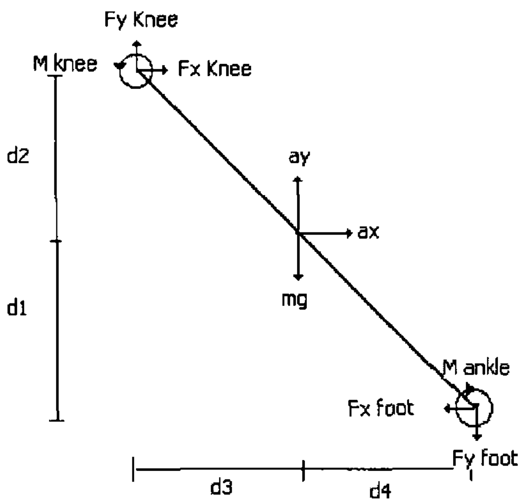
$F_y hip - F_y knee - mg = ma_y$

$F_y hip = ma_y + F_y knee + mg$

$\Sigma M = I\alpha$

$M_{hip} - M_{knee} - F_x knee\ d_1 - F_x hip\ d_2 + F_y knee\ d_3 + F_y hip\ d_4 = I\alpha$

$M_{hip} = M_{knee} + F_x knee\ d_1 + F_x hip\ d_2 - F_y knee\ d_3 - F_y hip\ d_4 + I\alpha$



$\Sigma F_x = ma_x$

$F_x knee - F_x foot = ma_x$

$F_x knee = ma_x + F_x foot$

$\Sigma F_y = ma_y$

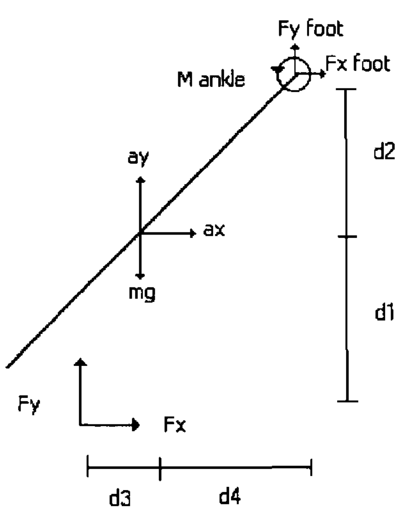
$F_y knee - F_y foot - mg = ma_y$

$F_y knee = ma_y + F_y foot + mg$

$\Sigma M = I\alpha$

$M_{knee} - M_{ankle} - F_x foot\ d_1 - F_x knee\ d_2 - F_y foot\ d_3 - F_y knee\ d_4 = I\alpha$

$M_{knee} = M_{ankle} + F_x foot\ d_1 + F_x knee\ d_2 + F_y foot\ d_3 + F_y knee\ d_4 + I\alpha$



$\Sigma F_x = ma_x$

$F_x foot + Fx = ma_x$

$F_x foot = ma_x - Fx$

$\Sigma F_y = ma_y$

$F_y foot + Fy - mg = ma_y$

$F_y foot = ma_y - Fy + mg$

$\Sigma M = I\alpha$

$M_{ankle} + Fx\ d_1 - F_x foot\ d_2 - Fy\ d_3 + F_y foot\ d_4 = I\alpha$

$M_{ankle} = -Fx\ d_1 + F_x foot\ d_2 + Fy\ d_3 - F_y foot\ d_4 + I\alpha$

EXCEL DATA FILTER CODE

Insert Raw data from VICON in csv format

```
Sub Filter()

'delete graphs after examining them

   Sheets(Array("LSHO", "RSHO", "LASI", "RASI", "LKNE", "RKNE", "LANK", "LHEE",
"LTOE", _
      "RANK", "RHEE", "RTOE")) Select
   Sheets("LKNE") Activate
   ActiveWindow SelectedSheets Delete

'filter the data
```

Sample filter (note first 4 data points do not use previous filtered data only raw)

```
=IF(LTOE_Z ="", "",  (0 006181*LTOE_Z) + (0 012361*[Raw data(LTOE_Z) – 1]) +
(0 006181*[Raw data(LTOE_Z) -2)+(1 7656*[filtered data(LTOE_Z) – 1])
+(-0 79034*[filtered data(LTOE_Z) – 2]))
```

```
   Dim intEntryCount As Integer
   Dim strCopy1 As String
   Dim strCopy2 As String

   intEntryCount = Range("B2") Value
      strCopy1 = "AV6 BN" & CStr(intEntryCount + 5)

   Range(strCopy1) Select
   Application CutCopyMode = False
   Selection Copy
   ActiveWindow ScrollRow = 1
   Range("BP6") Select
   Selection PasteSpecial Paste =xlValues, Operation =xlNone, SkipBlanks = _
      False, Transpose =False
   Application CutCopyMode = False
   Selection Sort Key1 =Range("BP6"), Order1 =xlDescending, Header =xlGuess _
      , OrderCustom =1, MatchCase =False, Orientation =xlTopToBottom

   strCopy2 = "CJ6 DB" & CStr( intEntryCount + 5)
   Range(strCopy2) Select
   Selection Copy
   ActiveWindow ScrollRow = 1
   Range("DD6") Select
   Selection PasteSpecial Paste =xlValues, Operation =xlNone, SkipBlanks = _
      False, Transpose =False
   Application CutCopyMode = False
   Selection Sort Key1 =Range("DD6"), Order1 =xlAscending, Header =xlGuess, _
      OrderCustom =1, MatchCase =False, Orientation =xlTopToBottom
```

Filter again (Sample filter)

```
=IF(LTOE_Z ="", "",  (0 006181*LTOE_Z) + (0 012361*[Raw data(LTOE_Z) – 1]) +
(0 006181*[Raw data(LTOE_Z) -2)+(1 7656*[filtered data(LTOE_Z) – 1])
+(-0 79034*[filtered data(LTOE_Z) – 2]))

End Sub
```

EXCEL CODE CALCULATION OF KINEMATIC AND KINETIC DATA

Import filtered data from filtering program

Sample calculation for data point 21

COPxd =IF(OR(R21="",V21=""),"",((P21*R21)+(T21*V21))/X21)
Foot Length =IF(Toe Y="", "", SQRT((Heel Y-Toe Y)^2+(Heel X-Toe X)^2))
Shank Length =IF(Ankle Y="", "", SQRT((Knee Y-Ankle Y)^2+(Knee X-Ankle X)^2))
Thigh Length =IF(Knee Y="", "", (SQRT((Hip Y-Knee Y)^2+(Hip X-Knee X)^2)))
Trunk Length =IF(Hip Y="", "", SQRT((shoulder Y-Hip Y)^2+(shoulder X-Hip X)^2))

Foot Angle =IF(Toe Y="", "", ASIN((Heel Y-Toe Y)/Foot_Length))
Shank Angle =IF(Ankle Y="", "", 3 141592654-ASIN((Knee Y-Ankle Y)/Shank_Length))
Thigh Angle =IF(Knee Y="","",(ASIN(Hip Y-Knee Y)/Thigh_Length))
Trunk Angle =IF(Hip Y="", "", 3 141592654-ASIN((shoulder Y-Hip Y)/Trunk_Length))
Ankle Angle =IF(Foot_Angle ="", "", (3 141592654-Shank_Angle)+Foot_Angle)
Knee Angle =IF(Thigh_Angle ="", "", (3 141592654-Shank_Angle)+Thigh_Angle)
Hip Angle =IF(Thigh_Angle ="", "", (3 141592654-Trunk_Angle)+Thigh_Angle)

AA Foot =IF(OR(AD20="", AD22 = ""), "", (AD22-(2*Foot_Angle)+AD20)/t^2)
AA Shank =IF(OR(AE20="", AE22 = ""), "", (AE22-(2*Shank_Angle)+AE20)/t^2)
AA Thigh =IF(OR(AF20="", AF22 = ""), "", (AF22-(2*Thigh_Angle)+AF20)/t^2)
AV Ankle =IF(OR(AH20="", AH22 = ""), "", (AH22-AH20)/(2*t))
AV Knee =IF(OR(AI20="", AI22 = ""), "", (AI22-AI20)/(2*t))
AV Hip =IF(OR(AJ20="", AJ22 = ""), "", (AJ22-AJ20)/(2*t))

Afx Foot Xd = COPxd
Afx Foot Y =IF(OR(Ankle Y ="",COPxd = ""), "", (((Ankle Y-Toe Y)/(Ankle X-Toe X)*(COPxd-Toe X))+Toe Y))
CoMFoot X =IF(Ankle X ="", "", 0 5*(Ankle X-Toe X)+Toe X)
CoMFoot Y =IF(Ankle Y ="", "", 0 5*(Ankle Y-Toe Y)+Toe Y)
Foot Vx =IF(OR(AT20 ="", AT22 = ""), "", (AT22-AT20)/(2*t))
Foot Vy =IF(OR(AU20 ="", AU22 = ""), "", (AU22-AU20)/(2*t))
Foot Ax =IF(OR(AT20 = " , AT22 = '), "", (AT22-(2*CoMFoot X)+AT20)/t^2)
Foot Ay =IF(OR(AT20 ="", AT22 = ""), "", (AU22-(2*CoMFoot Y)+AU20)/t^2)
Foot d1 =IF(CoMFoot Y="","",IF(Fyd>15,CoMFoot.Y,CoMFoot Y-Toe Y))
Foot d2 =IF(Ankle Y ="", "", Ankle Y-CoMFoot Y)
Foot d3 =IF(OR('Afx Foot Xd' ="", 'CoMFoot X' = ""), "", IF('Fyd'>15, CoMFoot X-Afx Foot Xd, CoMFoot Y-Toe X))
Foot d4 =IF(Ankle X ="", "", Ankle X-CoMFoot.X)

CoMShank X =IF(Knee X ="", "", 0 567*(Knee X-Ankle X)+Ankle X)

CoMShank Y =IF(Knee Y ="", "", 0 567*(Knee Y-Ankle Y)+Ankle Y)

Shank Vx =IF(OR(BD20 ="", BD22 = ""), "", (BD22-BD20)/(2*t))

Shank Vy =IF(OR(BE20 = '", BE22 = ""), "", (BE22-BE20)/(2*t))

Shank Ax =IF(OR(BD20 ="", BD22 = ""), "", (BD22-(2*CoMShank X)+BD20)/t^2)

Shank Ay =IF(OR(BE20 ="", BE22 = ""), "", (BE22-(2*CoMShank Y)+BE20)/t^2)

Shank d1 =IF(CoMShank Y ="", "", CoMShank Y-Ankle Y)

Shank d2 =IF(Knee Y ="", "", Knee Y-CoMShank Y)

Shank d3 =IF(CoMShank X ="", "", Ankle X-CoMShank X)

Shank d4 =IF(Knee X ="", "", CoMShank X-Knee X)

CoMThigh X =IF(Hip X ="", "", 0 567*(Hip X-Knee X)+Knee X)

CoMThigh Y =IF(Hip Y = "", "", 0 567*(Hip Y-Knee Y)+Knee Y)

Thigh Vx =IF(OR(BN20 = "", BN22 = ""), "", (BN22-BN20)/(2*t))

Thigh Vy =IF(OR(BO20 = "", BO22 = ""), "", (BO22-BO20)/(2*t))

Thigh Ax =IF(OR(BN20 = "", BN22 = ""), "", (BN22-(2*CoMThigh X)+BN20)/t^2)

Thigh Ay =IF(OR(BO20 = "", BO22 = ""), "", (BO22-(2*CoMThigh Y)+BO20)/t^2)

Thigh d1 =IF(CoMThigh Y = "", "", CoMThigh Y-'Knee Y')

Thigh d2 =IF(CoMThigh Y = "", "", Hip Y-CoMThigh Y)

Thigh d3 =IF(CoMThigh X = "", "", CoMThigh X-'Knee X')

Thigh d4 =IF(Hip X = "", "", Hip X-CoMThigh X)

Foot Fxp =IF(OR(Foot Ax = "", Fxd = ""), "", (Foot_Mass*Foot Ax)-Fxd)

Foot Fyp =IF(OR(Foot Ay = "", Fyd = ""),"", (Foot_Mass*Foot Ay)-Fyd+(Foot_Mass*9 81))

Foot Ialpha =IF(AA_Foot = "", "", Inertia_Foot*AA_Foot)

Shank Fxp =IF(OR(Shank Ax = "", Foot Fxp = ""), "", (Shank_Mass*Shank Ax)+Foot Fxp)

Shank Fyp =IF(OR(Shank Ay = "", Foot Fyp = ""), "",

(Shank_Mass*Shank Ay)+FootFyp+(Shank_Mass*9 81))

Shank Ialpha =IF(AA_Shank = "", "", Inertia_Shank*AA_Shank)

Thigh Fxp =IF(OR(Thigh Ax = "", Shank Fxp = ""), "", (Thigh_Mass*'Thigh Ax')+Shank Fxp)

Thigh Fyp =IF(OR(Thigh Ay = "", Shank Fyp = ""), "",

(Thigh_Mass*'Thigh Ay')+Shank Fyp+(Thigh_Mass*9 81))

Thigh Ialpha =IF(AA_Thigh = "", "", Inertia_Thigh*AA_Thigh)

M Ankle = -(Fxd*Foot d1)+(Foot Fxp*Foot d2)+(Fyd*Foot d3)-(Foot Fyp*Foot d4)+Foot Ialpha

M Knee =

M Ankle+(Foot Fxp*Shank d1)+(Shank Fxp*Shank d2)+(Foot Fyp*Shank d3)+(Shank Fyp*Shank d4)+Shank Ial pha)

M Hip = M Knee+(Shank Fxp*Thigh d1)+(Thigh Fxp*Thigh d2)-(Shank Fyp*Thigh.d3)-(Thigh Fyp*Thigh.d4)+Thigh Ialpha

P Ankle =IF(OR(AV_Ankle= "", M Ankle = ""), "", M Ankle*AV_Ankle)

P Knee =IF(OR(AV_Knee = "", M Knee = ""), "", M Knee*AV_Knee)

P Hip =IF(OR(AV_Hip= "", M Hip = ""), "", M Hip*AV_Hip)