Author(s): Robert Connell

Title: A kinematic analysis of the role of the upper-extremities during vertical jumping

Date: 2013

Originally published as: University of Chester PhD thesis

Example citation: Connell, R. (2013). *A kinematic analysis of the role of the upper-extremities during vertical jumping*. (Unpublished doctoral dissertation). University of Chester, United Kingdom.

Version of item: Amended version

Available at: http://hdl.handle.net/10034/326122

A KINEMATIC ANALYSIS OF THE ROLE OF THE UPPER-EXTREMITIES DURING VERTICAL JUMPING

Thesis submitted in accordance with the requirements of the University of Chester for the degree of Doctor of Philosophy

By Robbie Connell

SEPTEMBER 2013

Robbie Connell

A kinematic analysis of the upper-extremities during vertical jumping

Degree of Doctor of Philosophy in the Sport and Exercise Sciences Department

An original thesis submitted by Robbie Connell in accordance with the requirements of the University of Chester for the degree of Doctor of Philosophy.

I confirm that my dissertation does not contain any material that infringes any third-party copyright

(Signature)

ACKNOWLEDGEMENTS

Firstly, I would like to thank all the efforts made by my supervisory team, Dr Paul Worsfold, Dr Craig Twist and Dr Kevin Lamb, whose contribution to the completion of this thesis went above and beyond the usual requirements of a postgraduate research project. Thanks to you all.

I would like to say a special thanks to Dr Paul Worsfold, whose constant guidance and support throughout the whole of the last four years has helped me develop from an undergraduate to postgraduate researcher. Your patience during times of adversity genuinely kept me focused on completing this thesis.

Secondly, I would like to extend thanks to all the basketball players that participated in this study, especially to everyone who showed fantastic commitment during the upper-extremity plyometric programme during the final study in this thesis.

I would also like to thank the University of Chester Sport and Exercise Sciences Department for your continued contribution to my research, as well as offering me the opportunity to teach biomechanics during my postgraduate studies. In addition, I would like to extend special thanks to Matt Palmer and Yana Radcliffe for your technical support throughout this thesis, and your help in designing the modified bench and protocol used in study two.

To my family and friends who have supported me unequivocally throughout the whole of my postgraduate studies, I cannot thank you enough for your constant positive encouragement, and I hope the completion of this thesis is a big enough thank you to you all, especially for each and every one of your individual efforts of which there are far too many to list here.

And finally to my amazing girlfriend Lucy, without you I would never have completed this thesis, and I cannot wait to start the next chapter of our lives together. Thank you so much, and I am looking forward to giving you so much more of my time.

ABSTRACT

Over the last two decades, plyometric training has been extensively adopted by athletes, coaches and sport scientists with a primary aim to improve vertical jump height. The focus of these plyometric programmes has been to train the lower-extremity musculature in order to enhance jump performance. However, the lower-extremities are not the only contributing factor to vertical jump performance, as the use of an arm-swing during vertical jumping has also been shown to contribute to achieving maximum vertical jump height, yet training programmes for improving the arm-swing during the vertical jump are limited. Therefore, the primary aim of this thesis was to examine the full arm-swing mechanics during vertical jumping, and to then develop and assess the suitability of an upper-extremity plyometric programme for increasing both arm-swing kinematics and jump height. Firstly, a descriptive study was conducted to assess if an arm-swing countermovement was utilised during the vertical jump, which was deemed the prerequisite for using plyometric training to improve the arm-swing. Then an experimental study was conducted comparing vertical jumps performed with and without an arm-swing countermovement. The results showed that jumps performed with an arm-swing countermovement significantly increased mean peak shoulder angular velocity (ω) (+67.5 deg·s^{-1}) and mean jump height (+ 6.2 cm) when compared to jumps performed using no arm-swing countermovement. During the final chapter of this thesis, a group of elite basketball players volunteered to participate in upper-extremity plyometric training aimed at increasing vertical jump height by training only the upper-extremities. Vertical jump height and full body kinematics were analysed using a 3 dimensional (3D) motion capture system, and key kinematic jump variables and various arm-swing performance measurements were collated both before and after a 4 week upper-extremity plyometric intervention. The use of upper-extremity plyometric training significantly increased the mean jump height (+ 7.2 cm), mean peak shoulder ω (+ 167.1 deg·s^{-1}), mean peak frontal shoulder ω (+ 121 deg·s^{-1}) and mean active range of motion at the shoulder joint (+ 5.3°), when compared to a control group. Furthermore, the use of a large active range of motion arm-swing during the arm-swing countermovement was shown to be the preferred arm-swing condition for increasing arm-swing kinematics. The increase in arm-swing kinematics and jump height after the 4 week upper-extremity plyometric programme was attributed to the participants' improved ability to use the stretch-shortening cycle, elastic energy transfer system and stretch reflex system. Therefore, the use of upper-extremity plyometric exercises as part of a training regime for improving vertical jump performance should be advocated.

TABLE OF CONTENTS

List of figures 11

List of tables 15

Abbreviations...18

Chapter 1: Introduction

The vertical jump 21

Plyometric exercise 22

The arm-swing contribution to vertical jumping 23

Upper-extremity plyometrics 27

Aims and scope of the current research 28

Chapter 2: Review of literature

2.1 The countermovement action 33

Definition and mechanics of countermovement actions 33

The active state development in muscles within the lower body 34

An increase in actin-myosin interaction through the potentiation of the contractile components 38

The stretch reflex system and neuromuscular tendon stiffness 41

2.2 The countermovement action and the stretch-shortening cycle 45

The energetics of the stretch-shortening cycle 47

The stretch-shortening cycle during sport performance 50

2.3 Segmental contribution to vertical jump performance 53

The optimal coordination of moving segments..53

The role of the arm-swing during countermovement vertical jumping 57

2.4 Loading of the SSC during countermovement’s 67

Eccentric loading in the lower-extremities during jumping 67

Variable eccentric loading in the upper-extremities.......................................77

2.5 Plyometric exercise used to enhance the stretch-shortening cycle....81

Lower-extremity plyometric exercises..81

Upper-extremity plyometric exercises..89

2.6 Conclusions 93

Chapter 3: A kinematical analysis of the arm-swing countermovement during vertical jumping

3.1: Abstract 97

3.2: Introduction 98

Hypotheses 101

3.3: Methods 102

Participants and study design 102

Procedures 102

Two dimensional biomechanical model 103

Data processing 105

Key jump events and phases 106

Statistical analysis 107
3.4: Results 108
Key kinematic and kinetic descriptive 108
Jump kinematic correlations 111
Typical full body joint kinematics 112
Location of peak shoulder ω 114
3.5: Discussion 115
The arm-swing contribution during vertical jumping 115
Typical upper and lower-extremity mechanics..119
3.6: Conclusion 125

Chapter 4: The contribution of the arm-swing countermovement to vertical jump performance

4.1: Abstract 128
4.2: Introduction 129
Hypotheses 134
4.3: Methods 135
Participants and study design 135
Procedures 135
Data processing 137
Arm-swing countermovement specific phase 137
Statistical analysis 138
4.4: Results 138
Comparative arm-swing countermovement kinematic results 138
Peak jump height..139

Countermovement jump time and jump phase time 141
4.5: Discussion 144
4.6: Conclusion 153

Chapter 5: An investigation into the effects of a 4-week upper-extremity plyometric intervention on vertical jump performance in National League level male basketball players

5.1: Abstract 155
5.2: Part 1 Introduction 156
Hypotheses 158
5.3: Part 1 Methods 159
Participants and study design 159
Procedures 160
Arm-swing pre-test baseline measurements 162
Three dimensional high-speed kinematics 163
Upper body biomechanical model 164
Data processing 167
Statistical analysis 168
5.4: Part 1 Results 168
Collective pre-test arm-swing measurements 169
Comparative pre and post-test arm-swing kinematics 179
5.5: Part 1 Discussion 182
The optimal arm-swing conditions 183
Comparative pre and post-test arm-swing kinematics 187
5.2: Part 2 Introduction 191

Hypotheses 194
5.3: Part 2 Methods 195
Participants and study design 195
Procedures 195
Three dimensional high-speed kinematics.......................................196
Full body biomechanical model 198
Upper-extremity plyometric programme 198
Data processing 204
Statistical analysis 205
5.4: Part 2 Results 205
Full body arm-swing and jump kinematics 206
5.5: Part 2 Discussion 207
Vertical jump performance 209
Arm-swing kinematics during the vertical jump 212
5.6: Conclusion 216

Chapter 6

General Conclusions 218
Main findings 219
Limitations 224
Future directions 225

Chapter 7

References 229

Chapter 8

Appendices 256
Appendix 3.31 Ethical approval for Study 1..................................257
Appendix 3.32 Informed consent for Study 1................................258

Appendix 3.33 Pre-test health questionnaire one and two.....................259

Appendix 3.34 High speed camera calibration 262

Appendix 3.35 High speed camera positioning 263

Appendix 4.31 Ethical approval for Study 2...264

Appendix 5.31 Informed consent for Study 3........ 265

Appendix 5.32 Pre-test health questionnaire for Study 3........ 266

Appendix 5.33 Ethical approval for Study 3....... 269

Appendix 5.34 3D motion camera setup 270

Appendix 5.35 Upper-extremity plyometric programme 271

Appendix 5.41 Participants own choice of arm-swing 272

Appendix 5.42 Raw SPSS data and video files 273

LIST OF FIGURES

Figure 1.1 Flexion and extension phases within vertical jumping

Figure 1.2 Hierarchical vertical jump model (adapted from Hay & Reid, 1998)

Figure 2.1 The three key phases within a countermovement jump

Figure 2.2 The preparatory position for a countermovement jump and 3 variations of squat jumps

Figure 2.3 Graphs showing the ground reaction force trace and the vertical movement of the body's centre of mass during squatted exercises with and without a countermovement

Figure 2.4 Rectified and averaged EMG traces and ground contact phase for soleus activation during drop jumps from various heights with both legs.

Figure 2.5 Stretch-shortening cycle for the knee extensors during a countermovement jump

Figure 2.6 Countermovement mechanisms linked to the key components within the stretch shortening cycle (SSC) and the energies of the SSC

Figure 2.7 Four phases determining the key arm-swing events during CMJA

Figure 2.8 Starting position for squat jumps, with and without an arm swing

Figure 2.9 Optimal eccentric load conditions during the increase and decrease in Golgi tendon organ activation and utilisation of stored elastic energy

Figure 2.10 The ballistic six upper-extremity plyometric exercises

Figure 2.11 Plyoback ball return system

Figure 3.1 The arm swing contribution during countermovement jumps with an arm swing to increase the displacement of the body's centre of mass

Figure 3.2 Propulsive phases for a countermovement

Figure 3.3 Six segmental biomechanical model defined by seven anatomical landmarks

Figure 3.4 Reflective marker tracking through the transverse plane

Figure 3.5 Four phases determining the key arm swing events during countermovement jumps

Figure 3.6 Four key phases and five events for the arm swing during countermovement jumps

Figure 3.7 Typical (median) peak for the ankle, knee, hip, shoulder and elbow.

Figure 3.8 Digital and pictorial representation for the key events during the countermovement jumps (1-5)

Figure 3.9 Location for the mean peak at the shoulder joint

Figure 3.10 Location of individual peak shoulder values during countermovement jumps.

Figure 4.1 Arm countermovement during countermovement jumps

Figure 4.2 Arm start position for arm swings during countermovement jumps with and without a countermovement

Figure 4.3 Four phases determining the key arm swing events during countermovement jumps performed with and without a countermovement arm-swing.

Figure 4.4 Location for the mean peak at the shoulder joint during the CMJCA condition (arm down-swing, -0.008 s) and during the CMJNCA condition (arm up-swing, 0.028 s)

Figure 4.5 Location of individual peak shoulder values during CMJCA and CMJNCA

Figure 5.1 Schematic of study timeline (study 3)

Figure 5.2 Sub-maximal arm-swing plyometric exercise in two angled start positions

Figure 5.3 Modified weight bench

Figure 5.4 Laboratory set-up

Figure 5.5 Five segment biomechanical model (blue segments) defined by 35 anatomical landmarks

Figure 5.6 Upper body biomechanical model adapted from the UWA marker set

Figure 5.7 Estimation of the glenohumeral joint centre

Figure 5.8 The depth jump

Figure 5.9 Twelve segment biomechanical model

Figure 5.10 Full body biomechanical model

Figure 6.1 Movement pattern trace for the tennis serve

LIST OF TABLES

Table 2.1 Optimal eccentric load condition during squat jumps, countermovement jump and varied drop height drop jumps

Table 2.2 Mean (±) transition times (ms) during countermovement jumps and drop jumps from 30 cm with varied active range of motion (70° & 90°)

Table 2.3 Comparative studies for lower extremity plyometric programmes

Table 3.1 Mean values (±SD) for kinematic variables during a countermovement jump

Table 3.2 Mean values (±SD) for kinematic variables during a CMJA

Table 3.3 Mean values (±SD) for jump time and jump phase time percentages

Table 3.4 Pearson correlation coefficients (*r*) for key kinematic variables

Table 4.1 Comparative (lower extremity) studies for vertical jumping with and without a countermovement

Table 4.2 Values (±SD) for peak ω and peak location (phase) during both countermovement jumps with a countermovement arm swing and a countermovement jump without a countermovement arm swing

Table 4.3 Mean values (±SD) for maximum vertical displacement of hip marker during both countermovement jumps with a countermovement arm swing and a countermovement jump without a countermovement arm swing

Table 4.4 Mean values (±SD) for pre-test, utilised and percentage difference active range of motion during both countermovement jumps with a countermovement arm swing and a countermovement jump without a countermovement arm swing

Table 4.5 Mean values (±SD) for total jump time, time in each phase and percentage time in each phase (in respect to total jump time) during both countermovement jumps with a countermovement arm swing and a countermovement jump without a countermovement arm swing

Table 5.1 Peak ω differences between large and medium arm back-swings in the sagittal plane (shoulder flexion)

Table 5.2 Peak ω differences between medium and short arm back-swings in the sagittal plane (shoulder flexion)

Table 5.3 Peak ω differences between a 45 and 90° arm-swing start position in the sagittal plane (shoulder flexion)

Table 5.4 Peak ω differences between 67 and 84° trunk positions in the sagittal plane (shoulder flexion)

Table 5.5 Peak ω differences for concentric only arm-swings and the 45 and 90° start position arm-swings in the sagittal plane (shoulder flexion)

Table 5.6 Peak ω differences between large and medium arm back-swings in the frontal plane (shoulder adduction)

Table 5.7 Peak ω differences between medium and short arm back-swings in the frontal plane (shoulder adduction)

Table 5.8 Peak ω differences between a 45 and 90° arm-swing start position in the frontal plane (shoulder adduction)

Table 5.9 Peak ω differences between 67 and 84° trunk positions in the frontal plane (shoulder adduction)

Table 5.10 Peak ω differences for concentric only arm-swings and the 45 and 90° start position arm-swings in the frontal plane (shoulder adduction)

Table 5.11 Mean values (± SD) for pre and post-test peak arm-swing ω in the sagittal plane (shoulder flexion), for both the experimental and control groups

Table 5.12 Mean values (± SD) for pre and post-test peak arm-swing ω in the frontal plane (shoulder adduction), for both the experimental and control groups

ABBREVIATIONS

1 Rep max	1 maximal repetition
2D	2-dimensional
3D	3-dimensional
AROM	active range of motion
CMJ	countermovement jump
CMJA	countermovement jump with arm swing
CMJCA	countermovement jump with a countermovement arm swing
CMJNA	countermovement jump without an arm swing
CMJNCA	countermovement jump without a countermovement arm swing
COM	centre of mass
DJ	drop jump
E-C Coupling	eccentric-concentric coupling

EMG	electromyography
GRF	ground reaction force
GTO	Golgi tendon organ
KE	kinetic energy
PE	potential energy
SEC	series elastic component
SJ	squat jump
SJA	squat jump with arm swing
SJNA	squat jump without an arm swing
SSC	stretch-shortening cycle
UWA	University of Western Australia
VGRF	vertical ground reaction force
VJ	vertical jump

CHAPTER ONE

INTRODUCTION

The vertical jump (VJ) is a fundamental movement skill used in many sports such as basketball (Klinzing, 1991) and volleyball (Sheppard, Newton, & McGuigan, 2007). The ability to jump higher than opponents in basketball provides an advantage, improving a player's opportunity for rebounding, shooting, shot-blocking and dunking (Klinzing, 1991). The primary aim during vertical jumping is to achieve a maximum increase in the height of the body's centre of mass (COM) from a stationary position, that is, a maximal projection of the body's COM in the vertical direction. In essence, vertical jumping (Figure 1.1) is a movement characterised by a series of coordinated joint flexions (A1 to A2) and extensions (A2 to A3), respectively linked to the lowering and raising of the body's COM (Lees, Vanrenterghem & De Clercq, 2006).

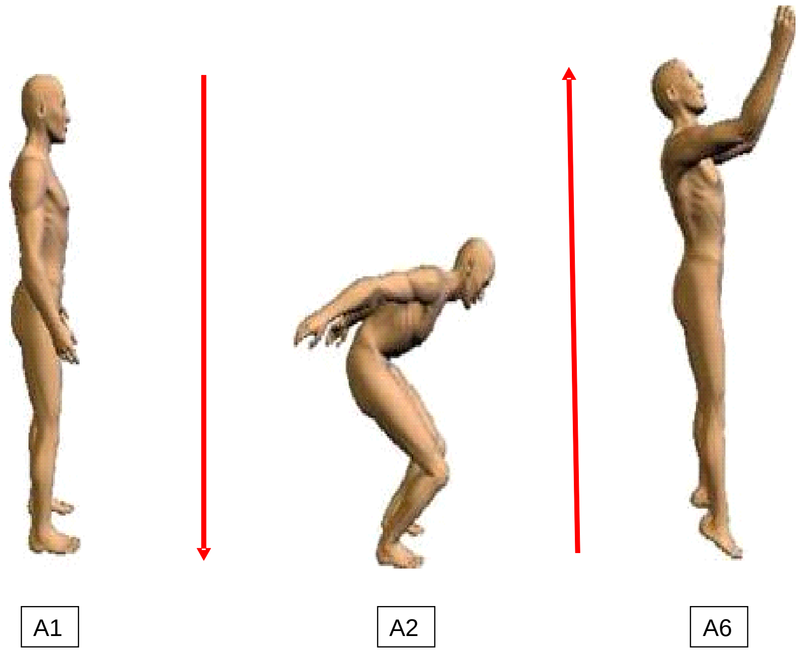


Figure 1.1 Flexion (A1-A2) and extension (A2-A3) phases within vertical jumping.

The lowering of the body's COM in the opposite direction to that of the intended movement (vertically upwards) defines a countermovement during vertical jumping, and when countermovement jumps (CMJ) are compared to vertical jumps performed with no preceding countermovement (starting in a squat position; see A2 in Figure 1.1), jump height has been shown to increase on average by 3.5 cm (McBride, McCaulley & Cormie., 2008; Gerodimos et al., 2008; Hara, Shibayama, Takeshita, Hay & Fukashiro, 2008). This suggests that a countermovement is one method that is utilised by athletes in an attempt to increase the vertical displacement of the body's COM, therefore increasing their overall maximum jump height.

The countermovement jump is a key performance indicator within many sports, both jump orientated (basketball and volleyball) and non-jump orientated (football and rugby), and various training methods have been developed, tested and utilised by sport scientists, coaches and athletes, all aimed at increasing jump height (Toumi, Best, Martin, Guyer & Poumarat, 2004; Lephart et al., 2005; Herrero, Izquierdo, Maffiuletti & Lopez, 2006). Plyometric exercises are the most commonly prescribed type of exercise for specifically improving CMJ performance, as they develop improvements in both the flexion (eccentric) and extension (concentric) phases of a CMJ. However, they are often used only as a secondary training modality for increasing jump height, supplementing the regularly prescribed weight programme interventions (Markovic, 2007; Innocenti, Facchielli, Torti & Verza, 2006; Moore, Weiss, Schilling, Fry & Li, 2007). Currently, the extensive body of research that has examined plyometric programmes has focused on the lower-extremity contribution to vertical jumping (Ronnestad, Kvamme, Sunde & Raastad, 2008; Ebben, Simenz & Jensen, 2008; Arabatzi Kellis, & Villarreal, 2010; Villarreal, Gonzalez-Badillo, & Izquierdo, 2009), identifying various mechanisms that are utilised by the legs to help improve jump performance. These are dominated by lower-extremity exercises primarily aimed at increasing speed and strength in the lower body musculature (Chu & Plummer, 1984; Holcomb, Lander, Rutland & Wilson, 1996). Conversely, a growing body of evidence (Lees, Vanrenterghem & De Clercq, 2004; Lees et al., 2006; Hara, Shibayama, Takeshita & Fukashiro, 2006; Walsh, Bohm, Butterfiled & Santhosam, 2007; Gerodimos et al., 2008) has argued that arm-swing contribution is just as vital in increasing jump height, demonstrated by an average percentage increase of 21.1% for jumps performed with an arm-swing compared to those with none.

When performing countermovement jumps with an arm-swing (compared to those with no arm-swing), the primary source for the increase in jump height has been demonstrated as the effective increase in vertical ground reaction force (VGRF) (Semenick & Adams, 1987; Hara et al., 2006), yet to date, investigators have only previously examined arm-swing mechanics in relation to the lower-extremities (lower-extremity propulsion). Interestingly, the most appropriate start position for examining a force time curve for the lower-extremities was previously defined at the point at when an athlete's COM reaches its lowest point (Feltner et al., 1999). However, this is not an accurate starting position for recording increases in VGRF, as this refers specifically to the increase in the propulsive element of VGRF. In contrast, an average force time curve clearly demonstrates that the major increase in VGRF occurs prior to this point, primarily increasing as a reaction to the braking force required by the lower-extremity muscles to overcome the lowering of the body's COM. Furthermore, the arms are highly active prior to the start of the lower-extremity propulsion (Feltner et al., 1999), so therefore may contribute to the braking force mechanics. A closer examination of the arm-swing during the braking phase element of a force time curve may help explain the increase in magnitude of instantaneous VGRF during this time and may improve our understanding of how the arm-swing initiates the VGRF increase (Lees et al., 2006; Hara et al., 2008).

Interestingly, during the early part of the jump (lowering of the body's COM), research has shown that increasing the magnitude of the countermovement, such as through increasing joint flexion at the hip (increased trunk inclination) and joint flexion at the knee, can lead to a subsequent increase in VGRF (Vanrenterghem, Lees & Clercq, 2008). Furthermore, the magnitude of the countermovement can be increased to a larger extent by increasing the velocity of the arm-swing, resulting in greater trunk inclination and a faster rate of knee flexion. Nonetheless, it appears that an improvement in both the upper and lower-extremities during a CMJ would result in the greatest increase in instantaneous VGRF, this is demonstrated by the hierarchical jump model (Figure 1.2) developed by Hay and Reid (1998).

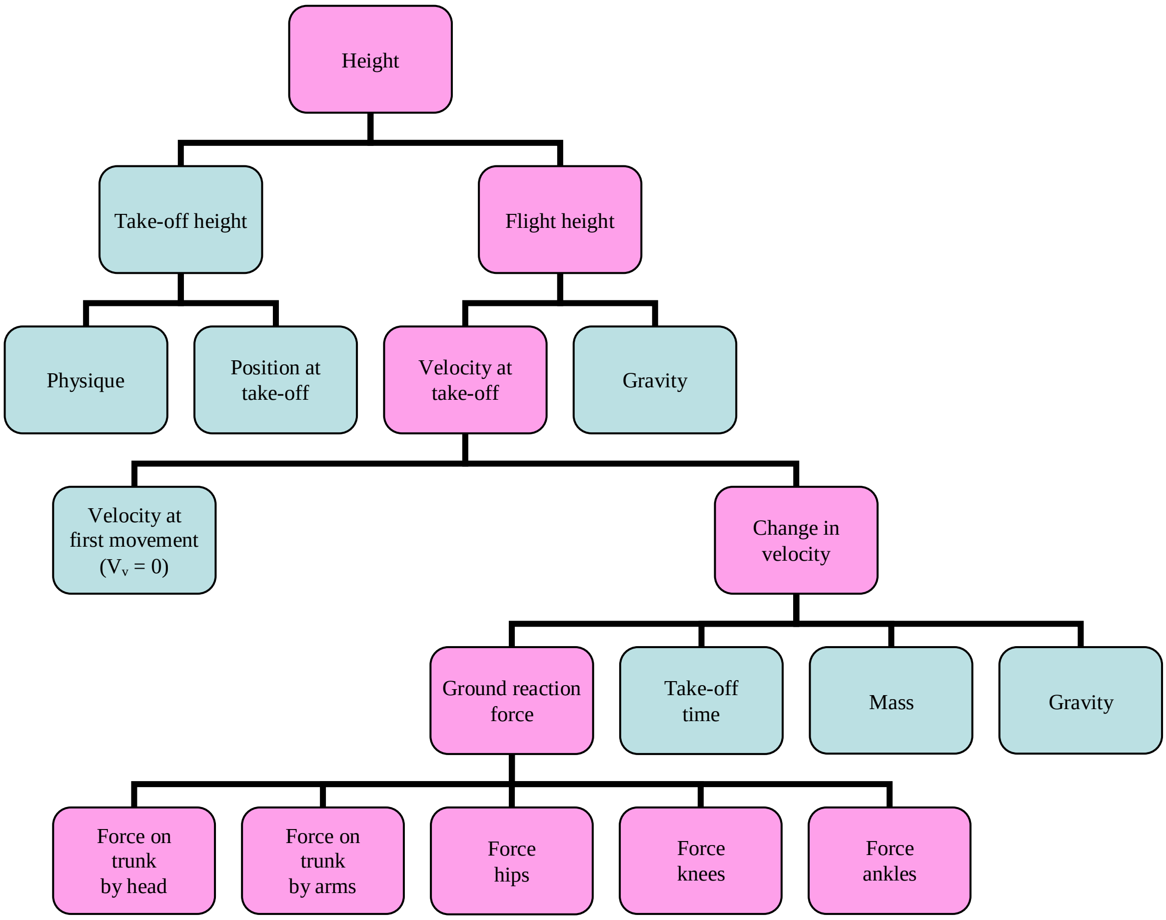


Figure 1.2 Vertical jump model adapted from Hay and Reid (1998). The pink pathway demonstrates a hierarchy for individual body segments to attain maximal ground reaction force.

The segmental breakdown during the final sector of the hierarchical model (Figure 1.2) indicates VGRF as a net result of the combined forces applied by the separate segments (force on trunk by head, force on trunk by arms, force at hips, force at knees and force at ankles). Interestingly, the model suggests that an increase in VGRF created by the arms acts directly upon the trunk, which supports the findings of Vanrenterghem et al. (2008) that an increase in arm-swing velocity would lead to an increase in trunk flexion (greater trunk inclination). Indeed, this would result in the body's COM being lowered both quicker (faster rate) and to a further extent (greater magnitude) suggesting that the countermovement phase of the jump would be improved. However, despite the upper extremities being identified as a vital component during the early part in a CMJ, research to date has continually focused predominantly on the role of the lower extremities. The full arm-swing mechanics during a CMJ have not been fully explored and warrant further investigation.

To develop arm-swing mechanics during a CMJ, investigators need to consider improving arm-swing kinematics (rate and magnitude of arm-swing) during the initial part of the arm-swing, especially as both the increase in trunk and knee flexion (lower-extremity countermovement) appear to be directly influenced by a faster arm-swing. Furthermore, the initial forward arm-swing movement is preceded by a large movement of the arms in the opposite direction (arm back-swing), suggesting that the arms utilise a countermovement similar to the legs during a CMJ. This could be a vital consideration to overall arm-swing mechanics, as previous comparative studies in the lower-extremities examining vertical jumps performed with (CMJ) and without (squat jump; SJ) a countermovement have demonstrated an average increase in VGRF of 9.6% during the eccentric braking phase of the force time curve, leading to an average increase in jump height of 7.4% after take-off (Bobbert et al., 1996; Bobbert et al., 2005; Walsh et al., 2007; Gerodimos et al., 2008; Hara et al., 2008; McBride et al., 2008; Earp et al., 2010). This indicates the same increase may be true for the arm-swing countermovement, yet it has never been examined and needs to be verified empirically. Furthermore, the proposed mechanisms for increasing the rate and magnitude of force and increase in jump height in the lower-extremities during CMJ performance, including the potentiation of the contractile components (Binder-Macleod et al., 2002), the stretch reflex system (Komi & Gollhofer, 1997; Laffaye, Bardy, & Durey, 2005; Gerodimos et al., 2008), the stretch-shortening cycle (SSC) (McBride et al., 2008; Gerodimos et al., 2008) and the effective storage and utilisation of elastic energy (Bobbert et al., 1996; McBride et al., 2008) need also to be considered.

An improvement in arm-swing kinematics during the arm-swing countermovement, such as the increase in angular displacement, velocity and active range of motion, could facilitate a positive change in the resulting subsequent forward arm-swing motion. That is, the arm-swing kinematics observed during the forward movement of the arms could be dependent upon what occurs previously during the arm-swing countermovement phase, and even though a preceding countermovement in the lower-extremities has been shown to increase the subsequent leg movement, this has never been examined in the upper extremities. Furthermore, by examining how a change in arm-swing kinematics during the arm-swing countermovement affects the resulting forward arm-swing, it will be possible to identify the optimal conditions for how a countermovement improves concentric performance.

The mechanics related to how a countermovement increases the subsequent desired movement is an important consideration in the development of plyometric programmes. Plyometric exercises utilise the stretch-shortening cycle (SSC) within the muscle being targeted, by increasing muscle pre-stretch during the countermovement (eccentric loading) and leading to an increase in concentric performance, as demonstrated during drop jumping (Chu, 1983; Chu & Plummer, 1984; Luebbers et al., 2003). Plyometric interventions used to increase jump height during a CMJ have been focused on lower body exercises, increasing both lower-extremity muscular power (Fatouros et al., 2000; Impellizzeri et al., 2008;

Marques et al., 2008; Arabatzi et al., 2010; Khlifa et al., 2010) and jump height (Bobbert et al., 1996; Villarreal, Kellis, Kraemer & Izquierdo, 2009; King & Cipriani, 2010).

The positive affect plyometric exercises have upon the increase in jump height during a CMJ is undisputed, however, various mechanisms have been posited in the literature as the primary source for this improvement, including the use of stored elastic energy (Sheppard, Newton & Mcguigan, 2007; Toumi et al., 2001; Lees et al., 2006), the contribution of reflex recruitment of additional motor units (Feltner et al., 2004; Harrison, Keane & Coglan, 2004; Myer, Ford, Brent & Hewett, 2006), joint coupling and coordination of muscle activation (Yamauchi & Ishii, 2007), increased rate coding (Jensen & Ebben, 2007; Markovic et al., 2007) and enhanced potentiation in the extensor muscles before ground contact (Young, Pryor & Wilson, 1995; Hennessy & Kilty, 2001). Previous investigators have achieved no consensus on which mechanism is primarily used during plyometric programmes, however, they have acknowledged the possibility these mechanisms work in collaboration. Consequently, the same mechanisms utilised during lower-extremity plyometrics could be utilised by the upper-extremities during upper-extremity plyometrics and justifies further exploration.

Research examining the use of upper-extremity plyometrics to improve sports performance is limited. Swanik et al. (2002) noted that the majority of upper-extremity plyometric programmes had only been advocated for use in rehabilitation; whereas, lower-extremity plyometric programmes had been developed for increasing sports performance. Swanik et al. (2002) indicated that plyometrics used for shoulder rehabilitation had shown improvement for shoulder kinematics, yet no suggestion was offered for how this could be applied in future studies which focused on performance instead of rehabilitation. Upper-extremity plyometric training was examined for baseball pitching (Carter, Kaminski, Douex-Jr, Knight & Richards, 2007; Fortun, Davies & Kernozck, 1998) and Judo throwing (Takahashi, 1992), aimed at improving upper-extremity kinematics. Carter et al. (2007) found that the plyometric shoulder exercises used for rehabilitation by Swanik et al. (2002) could be used in a ballistic manner to increase sports performance.

From an applied perspective, the exercises developed for improving throwing by Swanik et al. (2002) could be adapted as movement-specific exercises that replicate the arm-swing kinematics utilised during a CMJ. Furthermore, Carter et al. (2007) developed a set of six ballistic exercises that were movement specific to baseball pitching, leading to a 0.89 $m.s^{-1}$ increase in pitching speed, suggesting the same principle could be utilised when developing exercises that would mimic the arm-swing during a CMJ. The arm-swing during CMJ performance utilises a preceding countermovement in the opposite direction (countermovement), suggesting a loading phase and a subsequent propulsion phase similar to those observed in the lower-extremity countermovement's (Lees et al., 2004; Gamble, 2010). This indicates that shoulder movement characteristics during the arm-swing would utilise the muscles' SSC system (Knudson, 2003), and therefore may be suitable for training using an upper-extremity plyometrics intervention.

Aims of the current research

The principle aim of this research was to develop an upper-extremity plyometric programme based upon optimal upper body kinematics that would utilise movement specific exercises (arm-swing specific) and ultimately lead to athletes increasing their vertical jump ability by only training their upper-extremities. Previous researchers examining the use of plyometric exercises to improve vertical jump ability have focused their investigation upon lower-extremity plyometric programmes (Villarreal et al., 2009a; Villarreal et al., 2009b; King et al., 2010), demonstrating increases in jump height of up to 5.2 cm in just four weeks (Maffiuletti et al., 2002). However, the use of an arm-swing during vertical jumping has been shown to be of equal importance in improving jump height (Feltner et al., 2004; Hara et al., 2006; Lees et al., 2004), yet few studies have examined the use of upper-extremity plyometric exercises. The majority of upper-extremity plyometric programmes are prescribed for use in rehabilitation settings and demonstrate positive results for getting athletes back to full fitness following injury or surgery (Chmielewski et al., 2006). Yet upper-extremity plyometric exercises are rarely advocated for improving sports performance. A few studies have adapted upper-extremity rehabilitation exercises to be sport-specific, and when used in a ballistic manner have been shown to increase sports performance (Swanik et al., 2002; Carter et al., 2007). However, currently no research has developed movement-specific upper-extremity plyometrics that can be used to improve the arm-swing during vertical jumping. Positive improvements in jump height have been observed following a lower-extremity plyometric programme (Markovic, 2007); therefore, the current research aims to identify if similar improvements are evident upon completion of an upper-extremity plyometric programme. Conducting the current research without the addition of lower-extremity exercises will determine that any gains in jump height can be attributed solely to the improvements achieved in the upper-extremities.

Whilst previous studies have examined the arm-swing during countermovement vertical jumping (Feltner et al., 1999; Feltner et al., 2004; Hara et al., 2006), demonstrating an increase of 21.1% for jumps performed with an arm-swing compared to those without, none to date have examined the arm-swing mechanics throughout the whole jump. Moreover, other studies have suggested that the arm-swing during the early down-swing movement can help increase energy transfer (Lees et al., 2004; Lees et al., 2006), trunk flexion (Vanrenterghem et al., 2008) and increased SSC utilisation (Moran et al., 2007; McBride et al., 2008), yet none have examined the arm-swing mechanics prior to their forward swinging movement.

Therefore, the first study in this programme of research set out to investigate the arm-swing kinematics during the whole of a CMJ. In addition, a secondary aim of this study was to identify if an arm-swing countermovement is utilised during the arm-swing in vertical jumping.

Studies examining the use of a countermovement in the lower-extremities during vertical jumping have compared vertical jumps performed with and without the use of a countermovement, demonstrating an increase in jump kinematics when utilising a countermovement (Bobbert et al., 1996; Bobbert et al., 2005; Walsh et al., 2007; Gerodimos et al., 2008; Hara et al., 2008; McBride et al., 2008; Earp et al., 2010). Therefore, the aim of the second study was to investigate arm-swing kinematics during vertical jumps performed with and without an arm-swing countermovement. Additionally, Study Two set out to identify if any increase observed in arm-swing kinematics during the arm-swing countermovement condition materialised into improved lower-extremity jump kinematics.

Finally, Study Three comprised two research topics combined into one empirical study that investigated if upper-extremity plyometrics increase vertical jump height. Uniquely, Study Three used a batch of pre and post-test arm-swing movements in an attempt to highlight the optimal conditions required by the arm-swing during vertical jumping. Research has shown that the lower-extremities require a specific type of plyometric exercise to develop the greatest gains in jump height (Markovic, 2007), indicating there could be an optimal type of plyometric exercise to use. Furthermore, research examining the response of the lower-extremities' musculature to SSC type movements (the same movements utilised during plyometric exercises) has shown that movements with too high or too low SSC utilisation can actually have a negative effect upon concentric muscle performance (Moran et al., 2007;

McBride et al., 2008). Therefore, the batch of pre and post-test arm-swings utilised, included a wide range of low and high SSC utilisation aimed primarily at establishing which arm-swing condition was optimal. A final aim of Study Three was to examine if a change in arm-swing mechanics observed in the pre-and post-test arm-swing trials was responsible for any changes in jump height observed following the upper-extremity plyometric programme.

CHAPTER TWO

REVIEW OF LITERATURE

2.1 The countermovement action

Definition and mechanics of countermovement actions

A countermovement action is commonly used in sport to enhance performance (Gerodimos et al., 2008; Gamble, 2010). It is identified as a preceding movement occurring in the opposite direction to that of the desired action (Bobbert & Casius, 2005; Gamble, 2010). The countermovement 'loads' the athlete's musculature prior to a particular sporting movement (Lees, Vanrenterghem & De Clercq, 2006), such as a tennis serve (Elliott, Fleisig, Nicholls & Escamilia, 2003), golf drive (Fletcher & Hartwell, 2004), squash forehand (Elliott, Marshall & Noffal, 1996) or football throw-in (Marques, Marinho & Van Der Tillaar, 2010).

Sporting actions that utilise a countermovement can be broken down into three phases (Gerodimos et al., 2008). The preparatory action during Phase 1 (eccentric) refers to the actual countermovement and is linked with developing tension in a muscle whilst lengthening (eccentric muscle contraction). This is shown in Figure 2.1 by an example of a countermovement vertical jump (CMJ), often used as a performance indicator in

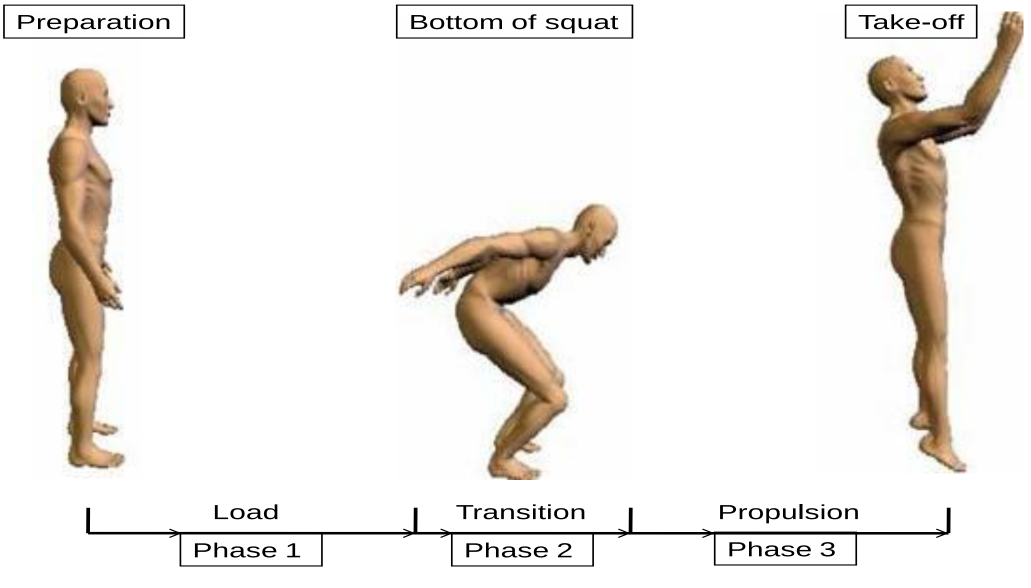


Figure 2.1 The three key phases with start and finish positions (Load, transition and propulsion) within a countermovement vertical jump (CMJ).

sports such as basketball and volleyball. Phase 1 movements are characterised by a series of coordinated joint flexions (hip, knee and ankle) coupled with shoulder hyper-extension (Preparation to Transition) (Brodt, Wagner & Heath, 2008), actively pre-stretching the upper and lower-body musculature. Active pre-stretch leads to an increase in muscular tension during the eccentric contraction at the shoulder (anterior deltoid), hip (gluteus maximus), knee (rectus femoris) and the ankle (gastrocnemius), and is referred to as the ‘loading phase’ (Bobbert et al., 2005), and interchangeably used with the term ‘preparatory phase’.

The second phase (‘isometric’) relates to the subsequent transition period, as muscle contraction is neither lengthening nor shortening (isometric muscle contraction). This is shown during the transition between countermovement and the proceeding action, termed eccentric concentric coupling (Kay, Mitchell, Lambert & Noakes, 2000). During the final (third) phase (‘concentric’) the muscles develop tension whilst shortening (concentric muscle contraction), and provide the main source of propulsion (Bobbert et al., 2005). Phase 3 movements are characterised by a series of coordinated joint extensions (hip, knee and ankle) coupled with shoulder flexion (Transition to Take-off) (Brodt et al., 2008). The increase in concentric performance when preceded by a loading phase is created by the pre-stretch in the muscles causing them to become more active, referred to as active state development in the muscles (Bobbert et al., 1996; Bobbert et al., 2005).

The active state development in muscles within the lower body

Bobbert et al. (1996) examined the contribution of the countermovement sequence to vertical jumping by comparing muscle activity, kinematic, and force production variables in jumps conducted with a countermovement (CMJ) and without the action (i.e. squat jump; SJ). They proposed that an increase in muscle activity during the eccentric phase of CMJ would improve muscular conditions during the subsequent concentric phase and lead to an increase in jump height. Six National League volleyball players performed randomised trials of a single variation of a CMJ and three variations of a squat jump (SJ-1, SJ-2 and SJ-3, Figure 2.2).

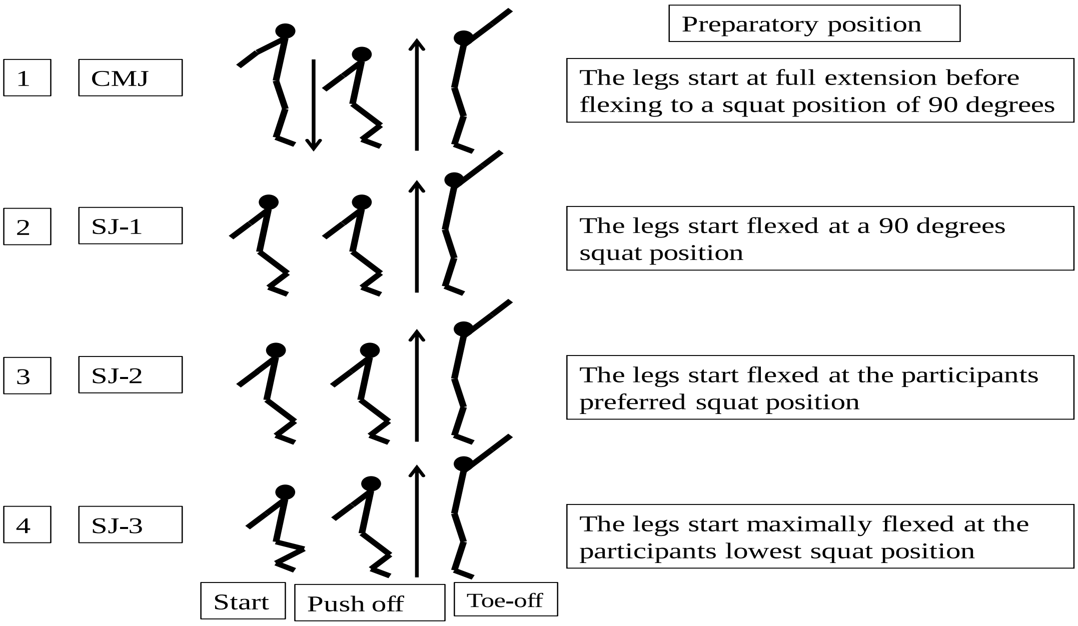


Figure 2.2 The preparatory position for a CMJ and three variations of SJ (Adapted from Bobbert et al., 1996).

The SJ isolated the countermovement in the legs (removing any enhancement that is achieved during the eccentric phase) enabling any improvements due to the countermovement to be measured during the CMJ. During all trials, the arms were positioned at the point of maximum shoulder hyper-extension until the start of the leg extension phase, and the trunk was maintained as close as possible to anatomically upright. Arguably, this should be criticised as changing the normal position of the trunk during each jump will have affected and altered normal jump mechanics. Performance of the countermovement was found to increase vertical jump performance when compared to a SJ, with average jump height being 3.4 cm more. This observation was similar to those in other studies that reported improvements of 3 to 5 cm (McBride et al., 2008; Gerodimos et al., 2008; Hara et al., 2008).

The most noticeable difference between the CMJ and SJ conditions was the magnitude of the GRF, which was larger during the CMJ. In particular, the CMJ GRF (1,708 N) was larger at the initial push-off phase (during early concentric performance) to all three squat jumps (1,006 N, 1,187 N and 905 N for SJ-1, SJ-2 and SJ-3, respectively).

McBride et al. (2008) observed similar findings when examining different eccentric loads during SJ, CMJ and drop jumps (DJ). Eight male and eight female National League basketball players performed five trials for the three jump conditions, with GRF collected from a single force platform. The results showed peak concentric force was dependent on an increase in eccentric load, demonstrating the greatest peak GRF during the DJ condition (DJ ≥ CMJ ≥ SJ). Bobbert et al. (1996) had earlier suggested that the increase in GRF occurred owing to the increase in the mean joint moments at the hip (+155 Nm), knee (+110 Nm) and ankle (+93 Nm), which in turn allowed more force to be produced at an earlier stage in the concentric muscle contraction. Moreover, surface electromyography (EMG) indicated that the muscle active state was lower prior to the start of the concentric phase in all three SJ conditions compared to CMJ. This finding suggests that the muscles were primed prior to shortening, creating a higher active state because of an improved actin-myosin interaction (Bobbert et al., 1996). Closer inspection of the individual muscle activity during the CMJ condition showed that both the rectus femoris (agonist) and vastus medialis (agonist) experienced their peak values during the countermovement phase (eccentric), but then decreased during the initial concentric phase. Arguably, the increased peak GRF must develop as a result of the increased eccentric activity and not the decreased concentric muscle activity.

Similar work by McBride et al. (2008) who analysed muscle activity for the vastus medialis, vastus lateralis and biceps femoris using surface EMG. Eccentric muscle activity increase was linked to the type of jump that demonstrated the larger amount of eccentric load, that is, DJ (highest level of eccentric load created from increased drop height) showed larger muscle activity than CMJ (eccentric load created only during leg flexion), and CMJ showed more than SJ (no eccentric load). This finding demonstrates a typical example of an athlete's increased requirement to use more muscle force during the braking phase of an increased countermovement. Findings suggested that an increase in eccentric muscle activity by way of increasing eccentric load develops advantageous conditions (increased cross-bridge attachment) in the musculature for increasing concentric force. Furthermore, the increase in muscle force appears to be time-dependent when comparing between jumps with and without a countermovement, meaning muscle force increases at varied rates dependent upon jump type, until maximum muscle excitation is achieved.

During maximum voluntary contractions, muscle excitation is not instantaneous and therefore muscles take time to develop force (Bobbert et al., 1996). Consequently, the SJ condition which has developed less muscle excitation (no eccentric phase) would not produce the same magnitude of force until a later part of the concentric phase; therefore, there would be a period of time (start of the concentric phase) where the muscles are contracting sub-maximally. Subsequent work by Bobbert et al. (2005) examined the 'active state development' within the lower-body muscles during CMJ and SJ performance, by comparing the muscle activity from a participant's jump data to that from a model of the musculoskeletal system. The simulation model comprising four rigid segments (trunk, thigh, shank and foot) and six muscle groups (gluteus maximus, rectus femoris, vastus medialis, hamstrings, gastrocnemius and the soleus) simulated the development of the active state in the muscles with no correspondence to any reflexes or potentiation. During the CMJ, muscles were activated prior to the SJ, which led to an increase in GRF and jump height in all trials. Their findings suggested that the increase in active state of the muscles during a countermovement increased the hip extensor moments, which in turn increased force production during the initial concentric phase and caused greater muscle excitation. Evidence suggests that the ‘active state’ development in muscles plays a vital role in increasing GRF during CMJ over SJ (Bobbert et al., 1996; McBride et al., 2008; Bobbert et al., 2008); however, there are several other key mechanisms that may contribute to the enhancement.

Alternative mechanisms for increasing the rate and magnitude of force and vertical jump height during CMJ performance include the potentiation of the contractile components (Binder-McCleod et al., 2002), the stretch reflex system (Komi & Gollhofer, 1997; Gerodimos et al., 2008), the stretch-shortening cycle (SSC) (McBride et al., 2008; Gerodimos et al., 2008) and the effective storage and utilisation of elastic energy (Bobbert et al., 1996; McBride et al., 2008).

An increase in actin-myosin interaction through the potentiation of the contractile components

Bobbert et al. (1996) described the potentiation of the contractile components during muscle pre-stretch as an important mechanism for increasing the rate and magnitude of force. Potentiation of a muscle fibre is the change or enhancement in force observed following activation (Takarada, Hirano, Ishige & Ishii, 1997). The grade of enhancement is affected by the amount of activation (frequency and duration), volume of nerve impulses and the activation stimuli and will vary under different degrees of muscle stretch (Edman, Elzinga, & Noble., 1982; Binder-McCleod, Dean & Ding, 2002). Takarada et al. (1997) examined stretch-induced (eccentric) muscle activity during countermovement squat performance using surface EMG, 2D kinematics and force analysis. Five male athletes performed 5 to 10 trials of a loaded squat (barbell weighing 50% of one rep max) with and without a countermovement, with muscle activity recorded from the vastus lateralis, bicep femoris and the lateral head of the gastrocnemius. Muscle activation during the loaded squat countermovement condition demonstrated peak activity during the eccentric phase, followed by a marked reduction during concentric performance, even though the GRF increased during this time (Figure 2.3). Typically, both graphs A and B show that during the concentric phase for both conditions, the vertical velocity of the body's mass (dotted lines) starts at zero in both conditions, however, the GRF observed at the start of the concentric phase was approximately 800 Nm higher in graph B.

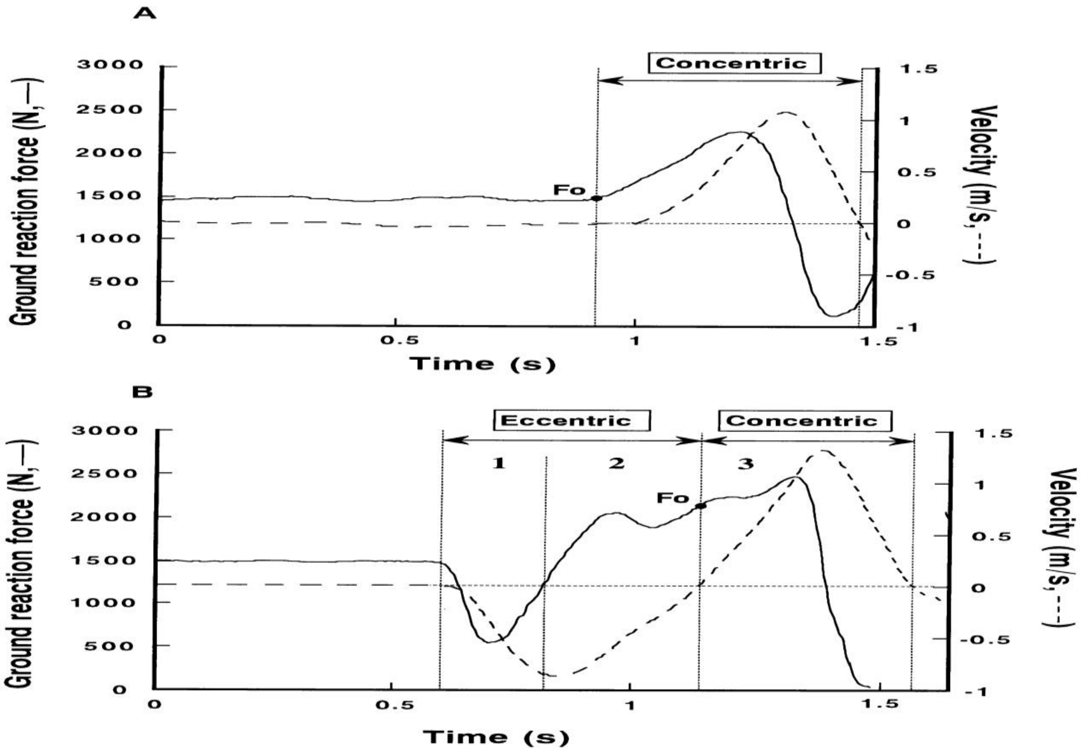


Figure 2.3 Typical graphs showing the GRF trace (solid line) and the vertical movement of the body's COM (dotted line) during squatted exercises without a countermovement (graph A) and with (graph B) a countermovement (Takarada et al., 1997).

The figures suggest that jumps performed without a countermovement are disadvantaged during the initial concentric push off, indicating a period of sub-maximal movement. Ground reaction force data demonstrated how a large negative force (lowering of the bodies COM) during the eccentric action (only during countermovement exercises) is subsequently followed by a ramped increase in GRF (a rapid deceleration counteracting the lowering movement), and when coupled with an increase in muscle activity, shows a similar trend to previous studies examining lower-body countermovement's (Bobbert et al., 1999; McBride et al., 2008).

When developing an 'active state' in the muscles, Takarada et al. (1997) suggest that the use of a countermovement initiates an increase in the recruitment of motor units, and the properties of the contractile element become altered as a response to the pre-stretch. During the large force exerted in the negative phase in the countermovement squat (lowering of the COM), the series elastic component (SEC) is stretched to a greater extent than the squat performed with no countermovement. Previous studies have indicated how repeated countermovement squat exercises can subsequently lead to an increase in muscle stiffness (Wilson, Murphy & Pryor, 1994), which in turn, increases the stretch of the contractile element, and consequently increases the force developed by the individual cross bridges. Such findings are consistent with Bosco et al. (1981), who identified an advantage of cross bridge attachment being that the myosin heads were forcefully rotated further backwards during increased eccentric loads. This would indicate a greater 'pull mechanism' within the contractile components; however, this could only occur for the duration of cross-bridge attachment (cross-bridge cycle time) and, therefore, a rapid transition between eccentric and concentric contractions during countermovement's should be advocated.

The transition time between eccentric and concentric contraction during lower-extremity SSC movement has been studied extensively (Komi et al., 1997; Ettema, 1996; & Bobbert et al., 1996). The enhancement for the contractile components may be to the detriment of any decrease in contraction coupling time (Edman et al., 1982), demonstrating the complexity of the balance between eccentric and concentric muscle performance. Furthermore, increased eccentric loading during countermovement's is favourable for improving concentric performance (Edman et al., 1982; Bobbert et al., 1999; McBride et al., 2008), yet conflicting research indicates a limit for the amount of required eccentric load (Ingen Schenau, Bobbert & De Haan., 1997a; Moran et al., 2007). This may explain how an increase in eccentric load that is too large may be limited by the stretch receptors or stretch reflex system (Komi & Gollhofer, 1997).

The stretch reflex system and neuromuscular tendon stiffness

Early work by Dietz, Schmidtbleicher and Noth (1979) described the role of stretch reflexes as a vital response mechanism to muscle pre-stretch, suggesting pre-activation in the muscle during an eccentric contraction increases concentric performance. The stretch (spinal) reflex is a spinal triggered neural mechanism that detects change in muscle length and then acts by increasing muscle stimulation during the muscle stretch (Hamill & Knutzen, 2010). The contrast in pre-stretch that is increased during CMJ, yet drastically attenuated during SJ, may suggest the spinal reflex as a significant contributor to increasing jump height (Bobbert et al, 1996). However, the problem has been proving to what extent the contribution of the stretch reflex makes during a CMJ. Ingen Schenau et al. (1997a) argue that the role of the stretch reflex during coupled concentric eccentric contractions was only apparent in exercises that demonstrated high eccentric loads, such as hopping and drop jumping (DJ), and was not evident during low eccentric loads observed during a CMJ.

During high eccentric load jumps such as DJ, alpha motor neuron activity is increased by stretch reflexes, indicating these types of jump as optimal for increasing the contribution from the stretch reflexes; However, too greater increase in eccentric loading also increases activity at the Golgi tendon organ (GTO) (Komi & Gollhofer, 1997). The stretch reflexes reaction to change in muscle length and tension, respectively, plays a vital role within the neural mechanism indicating enhancement as a product of increased muscle stretch. However, if the rate or magnitude of muscle stretch is too large, the GTO creates an opposing inhibitory mechanism reacting to excessive muscle stretch; that is, in the same muscle exhibiting high level pre-stretch, the GTO will induce muscle relaxation. Komi et al. (1997) agreed with the research by Ingen Schenau et al. (1997a) that similar stretch reflex contribution is not apparent for SJ and CMJ activities, as during low eccentric loads, a reduction in alpha motor neuron activity is observed, caused by the decrease in magnitude of muscle pre-stretch. Furthermore, as eccentric load increases during jumping, the stretch reflex contribution also increases, as shown in studies that examine DJ from increasing various box heights (Lees & Fahmi, 1994; Moran & Wallace, 2007; Ishikawa, Niemela & Komi, 2005).

An examination of EMG activation in the soleus identifies the contribution from muscle stretch reflexes during DJ (Komi et al., 1997). Figure 2.4 shows that as DJ height increases from 20 cm to 60 cm, the stretch velocity of the soleus increases with a leftward shift towards the ground contact phase, indicating that increased eccentric loading leads to an increase in the rate and magnitude in muscle activation. This would suggest that athletes who participate in jumping sports should train using DJ type exercises from maximum possible drop heights. However, the EMG activation pattern during the DJ from 80 cm demonstrates the stretch reflexes sensitivity to overloading in the soleus, as the pattern of activation becomes disorganised.

Figure 2.4 Rectified and averaged EMG traces, and ground contact phase (red dotted line) for soleus activation during drop jumps (DJ) from various heights with both legs (Komi et al., 1997).

The stretch reflex observed during DJ80 cm is harder to identify, meaning the muscle spindles are unable to facilitate the required amount of activation as shown in the drop jump heights with less eccentric loading (20, 40 and 60 cm). However, it may also demonstrate the inhibitory effect from the GTO mechanism, facilitating an inverse stretch-reflex (localised muscle inhibition) (Hamill & Knutzen, 2010). As DJ height increases past 60 cm, Komi et al. (1997) suggest that inhibitory neuron activity increases, therefore decreasing performance during the subsequent concentric phase.

Employing an optimal amount of eccentric loading is therefore an important consideration for training modalities that utilise increased eccentric loading, such as stretch-shortening cycle (SSC) movements and plyometric training. It may be suggested that exercises performed with excessive, or not enough eccentric loading could therefore cause a negative response to training. That is, exercises designed with too much or too little eccentric loading will utilise too much GTO activity (increased neuromuscular inhibition) or too little alpha motor neuron activity (decreased stretch reflex utilisation) respectively.

During prolonged high level eccentric load exercises such as DJ60 cm, muscles initiate mechanical changes in response to rapid eccentric stretching of the muscle (Komi et al., 1997). Work by Nicol, Avela and Komi (2006) indicated that repeated high level eccentric loading in the muscles actually changed the mechanical properties within the muscular-tendon junction, increasing muscle stiffness and resulting in greater mechanical responses to muscle pre-stretch. Early work by Gollhofer, Stronjnik, Rapp and Schweizer (1992) reported high levels of muscle pre-stretch during the eccentric phase for DJ, yet attenuated levels in CMJ and SJ; indicating that CMJ performance required a greater increase in eccentric pre-load before initiating an increase in neuromuscular stiffness.

Similar findings were also reported in the later work by McBride et al. (2008) who demonstrated pre-activity and eccentric phase muscle activity were both significantly increased in the DJ condition, when compared to CMJ and SJ. They surmised high eccentric loading as vital for increasing neuromuscular stiffness, as muscles and tendons reacted to increased muscle pre-stretch by developing stiffness in their structures, leading to an increased stiffness regulation in the muscular-tendon junction that could gain greater facilitation of the stretch reflex. However, McBride et al. (2008) argued these mechanical modifications were dependent upon a decrease in the transition time during eccentric concentric coupling, as when time is reduced between the initial stimulation of the stretch reflex (during muscle pre-stretch) and the subsequent increase in alpha motor neuron activity, facilitation of the stretch reflex becomes faster in what is termed a true ‘reflex arc’ (Hamill et al., 2010).

The amount of eccentric loading utilised during jumping coupled with fast transition periods between eccentric and concentric muscle performance are important considerations when designing jump training programmes. The use of DJ in these programmes should be advocated but drop height must be set to a suitable height to achieve maximum facilitation from the stretch reflex system, yet minimum facilitation from the GTO inhibitory system. Once this is achieved, athletes will benefit from these conditions for developing neuromuscular stiffness, which has been shown to be a positive muscular adaptation to plyometric training. Plyometric exercises utilise the SSC during eccentric loading, leading to an increase in concentric performance and a faster transition time. Therefore, to achieve maximum concentric performance during sporting actions, the use of a countermovement as part of a SSC type movement should be advocated.

2.2 The countermovement action and the stretch-shortening cycle

Vertical jumps can be performed with (countermovement jumps; CMJ) or without (squat jumps; SJ) the stretch shortening cycle (SSC). The SSC incorporates a dynamic pre-stretch during the muscle lengthening (eccentric) contraction coupled with a rapid transition time (amortization; Ettema, 1996) to muscle shortening (concentric) (McBride, McCaulley & Cormie, 2008; Gerodimos et al., 2008; Walsh, Bohm, Butterfield & Santhosam, 2007). The outcome of this action during CMJ is a greater force exerted during muscle shortening and a greater take-off velocity (Komi, 2000; Hamill & Knutzen, 2003). Figure 2.5 shows an example of a SSC movement for the agonist knee extensors (rectus femoris) during a CMJ, and demonstrates the type of muscle contraction occurring at different stages of the movement (eccentric→isometric→concentric).

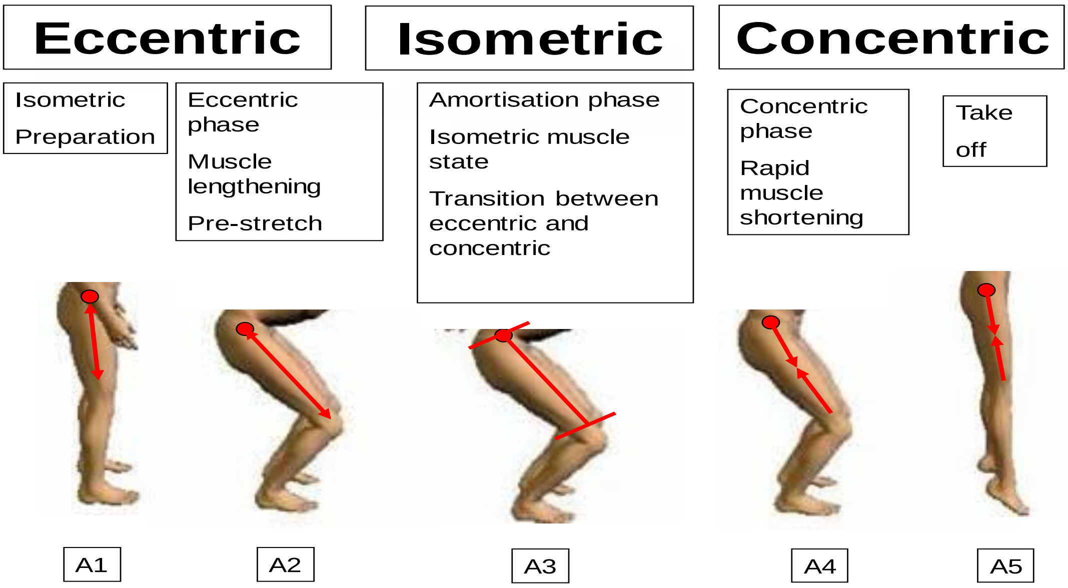


Figure 2.5 SSC phases (A1 to A5) for the knee extensors (rectus femoris) during a countermovement jump (CMJ).

The mechanisms responsible for the concentric enhancement during SSC movements have been debated in the literature (Ettema, 1996; Ingen Schenau et al., 1997a; Ingen Schenau et al., 1997b; Komi et al., 1997; Farley, 1997; Takarada, Hirano, Ishige & Ishii, 1997; Komi, 2000; Ettema, 2001; Nicol, Avela & Komi, 2006). Isolated muscle experiments have shown an increase in concentric performance when the muscle is actively pre-stretched prior to the concentric contraction (Cavagna, Dusman & Margaria, 1968; Cavagna, Komarek, Citterio & Margaria, 1971). Bobbert et al. (1996) indicated the primary mechanism for this enhancement was the increase in time available for force development during SSC movements, indicating an increased active state in the muscles following pre-stretch, leading to an increased rate of force development during the immediate concentric phase. This concept was examined by Ingen Schenau et al. (1997b) and Bosco (1997), who both agreed that muscle active state development was achieved during the pre-stretch in SSC movements. However, Komi et al. (1997) argued further that the concentric enhancement during SSC movements was primarily due to the role of the stretch reflexes, yet noted this was only true for high load SSC movements such as DJ, and not true for low load SSC movements such as the CMJ, as previously examined. Comparative studies have demonstrated an increase in concentric performance when utilising the SSC during CMJ (Bobbert et al., 1996; Bosco, 1997; Ingen Schenau et al., 1997), yet no consensus has been reached with regards to which mechanism acts as the main contributor during CMJ, however, the role of increased levels of elastic energy during countermovement's appears to be of importance in aspects of the proposed SSC theories

The energetics of the stretch-shortening cycle

Early work by Cavagna, Saibene and Margaria (1965) was the first to argue that stored elastic energy was the primary mechanism for the concentric enhancement in SSC movements, suggesting kinetic energy produced during an eccentric contraction can be stored and then reutilised during the concentric contraction. Kinetic energy is stored in the muscles as potential energy and produced as an elastic response caused by stretch in the muscle fibres (Tortora & Grabowski, 2003). The elastic properties associated with the mechanisms for the SSC system have been reported for CMJ (Bobbert et al., 1996; Gerodimos et al., 2008; McBride et al., 2008; Earp et al., 2010; Moran et al., 2007), and the majority of evidence suggests that an increase in kinetic energy production during a countermovement is subsequently stored in the series elastic elements awaiting reutilisation by the contractile elements (Lees et al., 2004; Lees et al., 2006; Anderson et al., 1993; Kubo et al., 1999). Conversely, work by Ingen Schenau et al. (1997) indicates the amount of kinetic energy reutilised during the initial concentric phase is proportional to muscle force and not to an increase in eccentric loading; thus, suggesting an increase in kinetic energy and the subsequent increase in concentric performance are not directly related. However, this should be treated with caution, as both storage and reutilisation of potential energy are highly functional during CMJ; yet, the difference in the increase of kinetic energy between CMJ and

SJ, and the source of this increase for both jump type remains questionable. Increased kinetic energy production during a countermovement occurs as a muscle response to bones rotating, indicating the muscle attachment to bone (rotating segment) reacting to muscle pre-stretch, and consequently creating an increase in kinetic energy (Lees et al., 2004; Hamill & Knutzen, 2009). During concentric only movements (SJ), there is no prior segment rotation to the concentric movement, suggesting the increase in kinetic energy production during SJ must be facilitated during the storage period (potential energy) and by a different method.

Ingen Schenau et al. (1997) argued kinetic energy production during SSC movements should not be ruled out as an enhancement mechanism, indicating positive relationships for potential energy reutilisation with CMJ (Prilutsky, 1997; Farley et al., 1997; Bosco, 1997; Minetti, Narici & Cerretelli, 1997) and running (Biewener, 1997). A response offered by Ingen Schenau et al. (1997) indicated that kinetic energy production increased proportionally to any increase in eccentric load, suggesting achievement of maximal concentric performance is determined by the achievement of maximal eccentric performance. Gerodimos et al. (2008) indicated that the transport of energy and the SSC were the leading explanation for how a countermovement increases VJ performance.

Lees et al. (2006) examined the transfer of energy in the upper-extremities during a downward swing of the arms. Twenty athletic male participants performed three trials each for three separate jump conditions with a normal arm-swing movement. Counter movement jump data were recorded with a force platform and a three-dimensional camera system for two variations of sub maximal (low and high) and a third variation of maximal (max) jumps. They indicated that a more forceful arm-swing led to greater increase in the build up of kinetic energy, which, in turn, led to an increase in storage and reutilisation of potential energy. Applied to the lower-extremities, this would suggest the eccentric phase loading can be increased by a faster countermovement prior to the transition phase (amortisation). Furthermore, the proceeding concentric contraction will be enhanced due to the increased level of potential energy available for reutilisation, supporting previous research that increased eccentric loading is correlated with an increase in CMJ height (Moran et al., 2007; McBride et al., 2008).

Further evidence exists in research on the storage and release of elastic energy in guinea fowl. Havalee, Ellerby and Marsh (2005) examined the jumping ability of guinea fowl and found they were able to produce power in excess of the amount available directly from the muscles. This suggests a secondary mechanism is available to amplify the power produced. The authors suggest a redistribution of the negative work (eccentric braking) achieved by the muscles must occur during the positive acceleration (concentric propulsion) of the leg muscles. The mechanism suggested for this redistribution is the effective storage, transfer and reutilisation of elastic energy. The authors noted that tendons are the most probable local storage site during the transition period, which agrees with the findings by Kubo, Kawakami and Fukunage (1999). They suggested tendon properties increase stiffness during CMJ which facilitates enhanced storage followed by an increased rate of recoil in the elastic energy. Ettema (1996) described the facilitation for storage and reutilisation of elastic energy as an ‘energy saving mechanism’, suggesting the transfer of energy makes the eccentric-concentric coupling more efficient. Anderson and Pandy (1993) argued that the primary use for storage and utilisation of elastic energy is in enhancing efficiency for CMJ performance instead of for directly improving maximum height, suggesting this mechanism is utilised more for sustainability during repeated jumps rather than contribution to explosive capability. Countermovement jumps utilised a different mechanism than SJ for increasing the amount of PE to be stored, by developing KE as a result of the skeleton ‘actively’ stretching the agonist extensor muscles during lowering of the body’s COM. In contrast the SJ develops kinetic energy as a result of contractile elements in the extensor muscles during an isometric contraction prior to concentrically contracting. However, the evidence suggests that irrespective of jump type (CMJ or SJ), the utilisation and transfer of kinetic energy is a vital component during jumping, and its contribution towards both the upper and lower-extremities requires further investigation (Kubo et al., 1999; Lees et al., 2004; Havalee et al., 2005; Lees et al., 2006). The relationship between SSC and the energetic of the SSC (see Figure 2.6) appear to be important considerations when examining the proposed mechanisms that create an increase in jumps that are performed with a countermovement compared to those that utilise none. It should be suggested that these mechanisms all work in collaboration, aimed at improving concentric muscle performance when increasing SSC utilisation during sporting movements.

Figure 2.6 Countermovement mechanisms linked to the key components within this cycle, the SSC and the energetics of the SSC (Bobbert et al., 2005).

The stretch-shortening cycle during sport performance

The SSC has been examined for its contribution to vertical jumping by comparing arm-swing jumps with (CMJA) and without (SJA) the action (Gerodimos et al., 2008). One hundred and six male basketball players performed three maximal jumps in both jump conditions with data collected from an optical jump mat. The contribution from the SSC was derived by the difference between CMJ and SJ performance. An increase of 3.2 cm (9.1%) was achieved when utilising the SSC in the CMJ condition compared to the SJ condition. Moran et al. (2007) argue that the increase in performance found during CMJ compared with SJ is sensitive to variable eccentric pre-loading. Seventeen elite male volleyball players performed twelve trials for each jump condition (SJ, CMJ and DJ) and a further two eccentric load positions per jump (70° and 90° knee flexion). An increase of 5.6 cm and 4.4 cm was observed between SJ and CMJ conditions with 70° & 90° knee flexion respectively. Furthermore, maximum VJ height increased by 5.4 cm from 70° to 90° knee flexion in the CMJ condition. The authors suggest that the SSC not only increases VJ height, the increase is determined by the amount of eccentric load. This indicates that any increase in rate or magnitude of SSC movement in the eccentric phase will be converted positively during the concentric phase.

Earp et al. (2010) examined the SSC during a CMJ with focus upon identifying the contribution from the lower-extremities muscle structure. Twenty five resistance trained males performed two sets of three trials in three jump conditions (SJ, CMJ & DJ). Force variables were collected using a force platform and synchronised with a single camera video analysis system. Ultrasonography was used to analyse muscle structure (fascicle thickness and pennation angle) for the vastus lateralis and the lateral gastrocnemius. CMJ technique was self regulated with arms akimbo, whereas SJ technique started at a position representative of the end of knee flexion during the CMJ with arms akimbo. The authors reported a 2.5 cm increase from SJ to CMJ performance and correlated ($r = 0.186$) this finding with fascicle thickness and pennation angle in the lateral gastrocnemius. A similar relationship ($r = 0.152$) was observed between the lateral gastrocnemius fascicle length and the difference in jump height between CMJ and DJ, suggesting that larger muscle lengths increased in jumps with greater amounts of eccentric loads, such as DJ in comparison to CMJ. Furthermore, the lateral gastrocnemius thickness was shown to be the best predictor of muscle power, suggesting that muscle thickness contributed mostly to eccentric muscle performance, and it was this that contributed greatest to increased SSC performance during the high eccentric load jumps (DJ).

McBride et al. (2008) indicate the SSC is dependent on the increase in eccentric muscle activity, as measured during the lengthening of the agonist muscle during a countermovement. Eight male and eight female National League basketball players performed 5 trials for three jump conditions (SJ, CMJ & DJ). Muscle activity was analysed using EMG from the vastus medialis, vastus lateralis and biceps femoris and force variables were collected from a single force platform. Eccentric muscle activity increased by jump type (DJ≥CMJ≥SJ) with the CMJ condition increasing in both eccentric muscle activity and jump height in comparison to SJ (41 cm ≥ 37 cm). However, no significant increase was demonstrated for jump height between CMJ and DJ (41 cm ≥ 40 cm) even though the eccentric activity of the agonist muscle (vastus lateralis) during the DJ was higher. Lees and Fahmi (1994) related this to deterioration in jump technique during greater eccentric loads. Moran et al. (2007) argued that an optimal ceiling for eccentric loads exists, whereby a load is reached that the musculature cannot support and deterioration in performance occurs.

The negative joint work observed during the eccentric phase of vertical jumping was examined by Hara et al. (2008). Five healthy males performed two variations of SJ with (SAJ) and without arm-swing (SJNA) and two variation of CMJ with (CMJA) and without arm-swing (CMJNA), therefore allowing the lower-extremity countermovement contribution to be compared to arm-swing contribution during jumps. Kinematic data were recorded using a single high-speed camera system and synchronised with force variables from a single force platform. The use of the SSC during the CMJ increased jump height compared to SJ both with arm-swing (58.0 ≥ 53.1 cm, CMJA and SJA respectively) and without arm-swing (49.3 ≥ 45.0 cm, CMJNA and SJNA respectively). Interestingly, SJA was higher than the CMJNA (53.1 ≥ 49.3cms) indicating that even though the lower-extremity SSC contribution increased jump height, the arm-swing demonstrated a greater contribution to jump height. Hara et al. (2008) suggested two possible ways in which the arm-swing was more effective, first by increasing the height of the body's centre of mass (COM), and secondly by creating an increase in the positive work achieved by the lower-extremity muscles during the concentric phase. This suggests another method in which the SSC mechanism can be loaded during a countermovement, by using upper-extremity rotation (trunk and arm-swing).

2.3 Segmental contribution to vertical jump performance

The optimal coordination of moving segments within a proximal to distal kinematic chain during countermovement jumps

Body segments that rotate in a proximal to distal sequence form a kinematic chain (Marshall & Elliott, 2000), in which athletes must coordinate and sequence each segment rotation correctly, ensuring the sequence follows the proximal to distal pattern (Feltner et al., 2004). Hara et al. (2006) suggest this pattern is evident in the lower body segments during CMJA, demonstrating a rapid triple extension of the joints starting at the hip and progressing distally through the knee and ankle. If the ankle is the final joint in the kinematic chain to initiate its peak rotation, this suggests the most distal segment is vital in maximising CMJA performance, mostly due to it being the final segment rotating prior to take-off. However, when multiple joint rotations exist as part of a kinematic chain, each proximal segment can influence the subsequent distal rotation, indicating that proximal segment rotation should be maximal in order to create maximal rotation in the distal joint (Feltner et al., 1999; Marshall & Elliott, 2000; Feltner et al., 2004).

Segment contribution to CMJA was examined by Vanrenterghem et al. (2008), who argued that trunk rotation was the proximal rotating segment to the lower-extremities during CMJA, and vital in changing the location of the body's COM. Twenty sub-elite athletic males performed three maximal CMJ with their arms on their hips coupled with their normal active range of motion (AROM) of trunk flexion. Once completed the participants then performed another three jumps with minimal trunk flexion (as close to 90° upright as possible). Trunk kinematics were analysed using a 3D motion capture system (240 Hz), and synchronised VGRF was collected using a single force platform (960 Hz). Increasing trunk flexion by effectively using an arm-swing during CMJ increased both maximum hip flexion (+27%) and maximum hip torque (37%), and subsequently led to an overall increase in jump height (44.4 ± 4.9 cm increased from 39.8 ± 3.9 cm). This suggests a direct relationship between trunk and hip kinematics, arm-swing kinematics and attainable jump height.

The increase in hip torque (+37%) during the normal trunk flexion jump condition accounted for a 10% increase in jump height, which is comparable to previous trunk inclination studies that observed 10% (Luhtanen & Komi, 1978) and 7.6% (Raven et al., 1999) increases when comparing CMJA with trunk flexion to no trunk flexion. Conversely, maximum knee flexion (-8%), torque (-19%) and power (-13%) all decreased, indicating the hip as the greater contributor to jump height. Interestingly, the reduction in knee flexion (-8%) during the normal trunk flexion condition would indicate a decrease in eccentric loading of the knee extensor muscles (rectus femoris), which according to findings by Moran et al. (2007), would effectively decrease jump height. A decrease in knee flexion would effectively decrease the range of motion in which the knee extensor muscles could develop pre-stretch, therefore reducing the muscle active state (Bobbert et al., 1996; Bobbert et al., 2005), and leading to a reduction in reutilisation of elastic energy (Lees et al., 2004) and the facilitation of the stretch reflex system (Komi et al., 1997). However, despite the negative impact created at the knee joint by an increase in trunk flexion, Vanrenterghem et al. (2008) demonstrated that trunk rotation could still increase jump height (+10%), suggesting that even with a decrease in both the flexion and extension phases of the knee, an increase in hip flexion and extension will still increase jump height.

The results highlight the importance of trunk rotation during CMJA performance. Furthermore, Vanrenterghem et al. (2008) examined trunk rotation to measure its segmental contribution within the CMJA kinematic chain, yet failed to acknowledge the role of the arm-swing. If the arms are the proximal rotating segment to the trunk during CMJA, then their effect will directly impact upon the rotation of the trunk, as increasing arm-swing rotation will increase trunk rotation. In both jump conditions, participants were instructed to hold their arms on their sides (hands on hips). Therefore, as the arms effectively increase the rate of trunk rotation, the jump condition with greater trunk rotation (full flexion) would normally develop faster trunk rotation, so when performed without the arms, this condition would demonstrate a larger decrease in the speed of trunk rotation. This demonstrates how the arm-swing plays a vital role in actively positioning adjacent body segments, and how this occurs during the early phases of a jump.

Arm swing

Ashby and Heegaard (2002) identified that the arm-swing increased the rate and magnitude of trunk flexion during CMJA. The increase in trunk flexion when using an arm-swing led to a 16.6% increase in horizontal displacement of the body’s COM. Similar findings were reported by Lees et al. (2004) noting an increase in magnitude (+ 5°) and rate (- 4%) of trunk flexion during CMJA compared to a no arm-swing jump condition. Vanezis and Lees (2005) argued that segmental positioning of the trunk occurred earlier during the CMJA condition, than when compared to jumps performed with no arm-swing, and the increase in trunk inclination would effectively lead to an increase in the amount of time available to extend the hip and trunk, and consequently lead to an increase in force. Therefore, an increase in arm-swing rotation (proximal) effectively increases trunk rotation (distal), leading to an increase in the rate and magnitude of trunk flexion, and the increase in both the force and velocity at the hip joint, effectively leading to greater power at the hip joint (+37%). The evidence indicates the trunk as the proximal segment to the legs in the kinematic chain during CMJA, and an increase in trunk flexion leads to the subsequent increase in hip flexion and jump height (Ashby et al., 2002; Lees et al., 2004; Vanezis et al., 2005; Vanrenterghem et al., 2008). Interestingly, the same principle applies to the arms, as they act as the proximal rotating segment to the trunk and therefore an increase in arm-swing velocity should lead to an increase in hip flexion and the subsequent trunk rotation. However, this has never been tested empirically and warrants further investigation. The arm-swing during CMJA demonstrates a vital role in segmental positioning, as well as acting as the initiator in the proximal to distal sequence of joint rotation within a kinematic chain during CMJA (Vanezis et al., 2005).

The initial arm-swing rotation creating hip flexion is created by shoulder hyper-extension (arm-swing countermovement), suggesting the back-swing of the arms as a vital component in increasing the rate and magnitude of trunk flexion (Vanrenterghem et al., 2008). This suggests a proximal to distal loading pattern, meaning the proximal segments initially rotate in the opposing direction to create increased pre-stretch in the agonist musculature during joint flexion. Therefore, arm-swing rotation and the subsequent trunk rotation need to be considered not only in the propulsive phase during CMJA, but also during the loading phase when an increase in shoulder hyper-extension and the opposing hip flexion, will increase the rate of flexion at the hip, knee and ankle (lower-extremity loading). However, the mechanics of the arm-swing during the arm-swing countermovement phase of the jump have not been fully explored, and this warrants further investigation.

The role of the arm-swing during countermovement vertical jumping

It is well established that the swinging and upward movement of the arms helps increase the vertical motion of the body’s centre of mass (COM) (Luhtanen & Komi, 1979; Shetty & Etnyre, 1989; Dapena, 1993; Lees & Barton, 1996). Feltner, Fraschetti and Crisp (1999) further suggested that the arms played a major role in creating a large vertical velocity of the body’s COM. Comparative arm-swing contribution studies have examined CMJ with (CMJA) and without an arm-swing (CMJNA), demonstrating an average increase in jump height of 21.4% during CMJA (Lees et al., 2004; Lees et al., 2005; Walsh et al., 2007; Gerodimos et al., 2008). Furthermore, the increase in jump height is consistent for arm-swing jumps with no lower-extremity countermovement. Hara et al., (2006) and Hara et al., (2008) reported an increase of 22.7% and 17.6% respectively, when comparing squat jumps with (SJA) and without an arm-swing (SJNA). However, the average lower-extremity contribution to jump height is only 7.4% (Bobbert et al., 1996; Bobbert et al., 2005; Walsh et al., 2007; Gerodimos et al., 2008; Hara et al., 2008; McBride et al., 2008; Earp et al., 2010), when compared to the 21.4% demonstrated by the upper-extremities.

In previous attempts to measure arm-swing contribution during CMJA, researchers analysed the arm-swing during key phases that are related to the mechanics of the lower-body (Feltner et al., 1999; Lees et al., 2004), and not specific to the starting position of the upper-body arm-swing, suggesting that important arm-swing mechanics may have been overlooked. Moreover, previous research has selected the start period for the analyses of the arm-swing contribution to occur mid-way through the arm-swing, at the position immediately prior to the start of the leg extension (Feltner et al., 1999; Lees et al., 2004; Hara et al., 2006; Hara et al., 2008). Whilst Feltner et al. (1999) argued that this was the most appropriate start position, as it referred to the moment of zero vertical velocity (eradicating any contribution from the lower-extremity countermovement), the propulsive phase (extension phase) for the lower body starts late in relation to the whole jump, occurring during the final phase. Conversely, the arm-swing and trunk movement appear to be highly active prior to this phase, though this has yet to be verified empirically and warrants further investigation.

Work by Feltner et al. (2004) argued that lower-extremity segment rotation (triple extension) was the primary source of propulsion during CMJA; and even though this is true, the authors failed to acknowledge the increase in VGRF prior to the starting point of the leg propulsive phase. At the start position for lower-extremity propulsion, upper-extremity (trunk and arm segments) rotation has already changed the position of the trunk, demonstrated by increased trunk inclination coupled with the arms rotating around the trunk from a point of maximum shoulder hyper-extension (Lees et al., 2004; Hara et al., 2006; Hara et al., 2008; Vanrenterghem et al., 2008). Propulsion was being created by upper-extremity segment rotation during the initial two jump phases, Phase 1 (arm back-swing) and 2 (arm down-swing), respectively (Figure 2.7) thus demonstrating the high activity of the arms during these phases in CMJA (Feltner et al., 1999; Lees et al., 2004) and warrants further investigation.

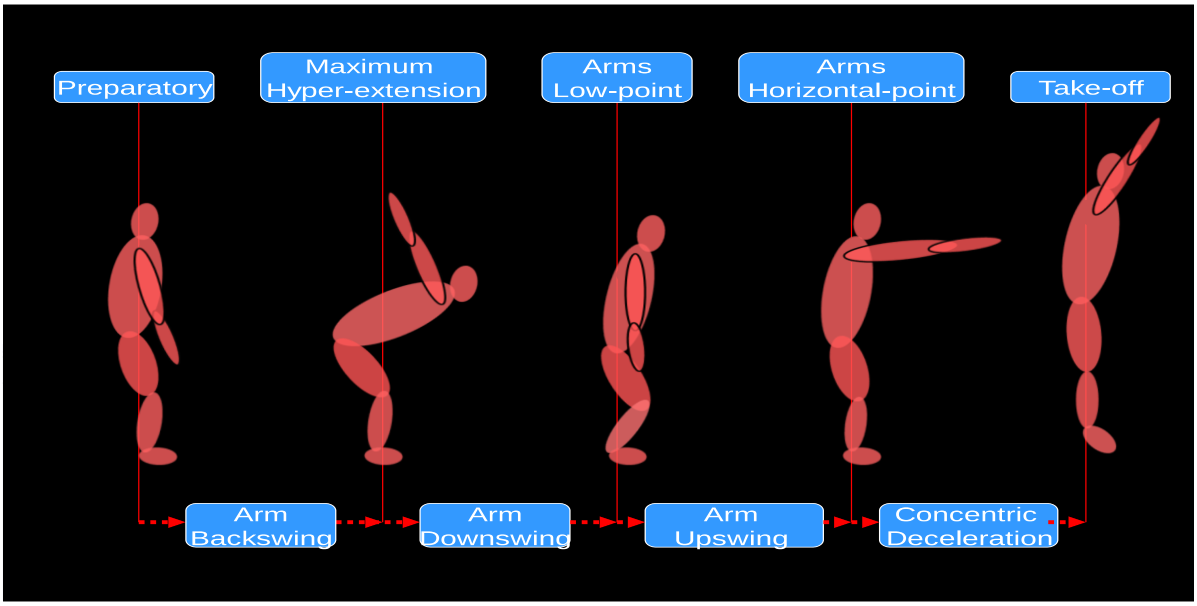


Figure 2.7 Four phases determining the key arm-swing events during CMJA (adapted from Feltner et al., 1999; Lees et al., 2004).

Feltner et al. (1999) examined the contribution of the arm-swing during CMJA. Twenty five national league volleyball players (14 male and 11 female) performed five randomised trials for both a CMJ with (CMJA) and without (CMJNA) an arm-swing. A six segmental biomechanical model was defined by nine anatomical landmarks using reflective markers, and trials were videoed using two synchronised cameras (60 Hz and 1/1000 s). Additionally, the vertical component of GRF and centre of pressure was simultaneously recorded using a single force platform (1000 Hz). A 14.3 cm increase in the vertical displacement of the body's COM was observed when utilising a CMJA compared to a CMJNA. Furthermore, the CMJA condition increased the vertical velocity of the body's COM at take-off (+0.31 m/s), as well as increasing the maximum vertical acceleration of the arm (+63.8 m/s), head and trunk (+2.1 m/s) and the head, trunk and arm segments (+2.4 m/s). The 14.3 cm increase in jump height was attributed to two mechanisms, a change in the position of the body's centre of mass (COM) and the effective increase in VGRF (Feltner et al., 1999; Walsh et al., 2007; Gerodimos et al., 2008).

Raising the arms above the head during CMJA effectively increased the height of the arm-segment mass, which in turn increased the location of the body's COM. In comparison to CMJNA, the use of an arm-swing during CMJA increases the height of the COM at take-off by 43% (Feltner et al., 1999). Conversely, the increase in VGRF must be attributed to the result of jump mechanics occurring prior to take-off, as the increase in VGRF is not instantaneous, therefore must increase prior to the point in which the maximal value is observed (Feltner et al., 1999; Feltner et al., 2004; Lees et al., 2004; Hara et al., 2008). Interestingly, the transmission of force theory suggests that as the arms are travelling upwards during CMJA, an opposing downward force travels in the vertical direction back through the body, effectively increasing VGRF (Payne et al., 1968). This suggests the increase in VGRF could be influenced by the arm-swing. However, a more convincing argument is that as the arm-swing travels downwards during the early phases of the jump, the downward motion of the arm-swing creates an opposing force on the lower-extremities, as the leg muscles contract during the lower-extremity loading phase (Moran et al., 2007). Notwithstanding this, there are also complex variables such as timing, coordination and subject population to consider, especially as each individual subject will have different abilities in each of these areas.

Furthermore, this would suggest that if the arm-swing was increased during the downwards motion, the opposing vertical force in the lower-extremities would also increase, suggesting a possible relationship between lower-extremity kinematics and the downward motion of the arm-swing. Furthermore, lower-extremity loading occurs prior to the leg propulsive phase, and also during the arm-swing phases that have not yet been fully explored, providing further evidence to why the early phases of a CMJA (Phase 1 and Phase 2) have not been empirically examined. This should be criticised as the increase in VGRF contributes 57% towards the increase in the displacement of the body's COM during the CMJA condition, accounting for an average increase in VGRF of 9.6% (Feltner et al., 1999; Feltner et al., 2004; Lees et al., 2004; Walsh et al., 2007; Hara et al., 2008) and demonstrates the importance of fully understanding the mechanics of the arm-swing during the whole jump, and not just in relation to the lower-extremities.

Lower body segment rotation

Feltner et al. (1999) considered a decrease in hip extensor torque as a contributing factor to the subsequent increase in VGRF, arguing that both force and velocity produced by the lower-extremities are directly influenced by the mechanics of the arms, and as arm-swing velocity increases, the time available at the hip, knee and ankle to produce force also increases. The arm-swing repositions the body's centre of mass (COM), initiating trunk flexion as the arms are drawn backward (Ashby et al., 2002; Lees et al., 2004). As the arms swing forward to their lowest point, the trunk rapidly extends, before decreasing in velocity prior to the leg propulsive phase (Vanrenterghem et al., 2008). This has the effect of slowing the rate of hip extension, developing advantageous conditions in the lower-extremity musculature for producing force. Therefore, it should be argued that how the arm-swing acts upon the lower-extremities prior to the decrease in the rate of hip extension is vital for improving lower-extremity kinematics during CMJA, and this adds further justification for why the arm-swing needs further exploration during the early jump phases.

Later work by Feltner et al. (2004) examined hip extensor torques for fifteen males with experience in a competitive jumping sport. Five randomised trials of CMJ were performed with and without an arm-swing, and twenty-five reflective markers located on key anatomical landmarks were used to identify a six segmental biomechanical model, and recorded using a motion capture system (120 Hz). Additionally, VGRF and centre of pressure data were collected using a single force platform (1000 Hz) and reported in respect to a four phase jump schematic adapted from their previous work (Feltner et al., 1999). In comparison to CMJNA, the use of an arm-swing during CMJA increased VGRF by 9.3 %, agreeing with their previous findings of 9.6 % and suggests that the arm-swing plays a vital role in increasing jump height even in elite jumpers (Feltner et al., 1999). Feltner et al. (2004) describe the arm-swing as going through a rapid acceleration during the early leg propulsive phase, subsequently followed by a rapid deceleration. During this phase, the extensor muscles at the hip, knee and ankle had opposite torques that decreased as the arms accelerated, and increased as the arms decelerated.

This could possibly indicate that if the arm-swing was increased to a greater extent during CMJA, then the opposing torques observed in the lower-extremities would also decrease further, suggesting that an increase in arm-swing velocity will result in better lower-extremity kinematics during CMJA. Earlier work by Feltner et al. (1999) highlighted similar finding during this time; suggesting that even though the torques at the hip, knee and ankle were decreasing during the early leg propulsive phase, this had no effect upon the athlete's ability to continue increasing VGRF. Therefore, it should be argued that an increase in arm-swing velocity should be advocated during CMJA, and this increase should occur prior to the point at which the lower-extremities begin their propulsive phase. This phase of the arm-swing refers to the downward motion of the arms and has been examined before, and warrants further investigation.

A decrease in extensor torque at the hip indicates an increase in the duration of time available for the leg propulsive phase during CMJA. Furthermore, this is coupled with a delay in muscle recruitment of fast twitch muscle fibres of the hip extensors (Feltner et al., 2004). The CMJ with no arm-swing creates less trunk inclination therefore initiating early muscle excitation in the leg muscles to act as a counterbalance to squatting in a more upright position (Vanrenterghem et al., 2008). In turn, this forces the fast twitch motor units to fatigue too early in the leg propulsive phase. During the CMJA condition, the hip extensor muscles are able to delay this recruitment, acting as an enhancement mechanism to allow a faster and more powerful delayed contraction to be utilised during the late-mid to late propulsive phase (Feltner et al., 1999). The results suggest that the arm-swing enhances the conditions of the lower-extremities for producing increased muscle force, allowing the greatest increase in force to be produced in the latter stage of the propulsive phase for the legs. Feltner et al. (2004) indicate that hip extensor torque is directly influenced by an increase in arm-swing rotation and the subsequent trunk rotation, suggesting the proximal to distal sequencing of segment rotation as vital in developing the optimal conditions for a decrease in hip extensor torque.

Proximal to distal sequence

The proximal to distal transfer of segment rotation during CMJA has been examined for both the upper and lower-extremities (Feltner et al., 2004; Lees et al., 2004; Hara et al., 2006; Vanrenterghem et al., 2008). Hara et al. (2006) examined proximal to distal segmental transfer for squat jumps with (SJA) and without (SJNA) an arm-swing. Five healthy males performed four randomised trials of each jump condition (Figure 2.8) and VGRF data was collected using a single force platform (200 Hz). A single high speed camera (200 Hz) recorded kinematical data for a six segment biomechanical model defined by seven anatomical joint markers located on the right side of the body.

Figure 2.8 Starting position for squat jumps with (SJA) and without (SJ) an arm-swing (Hara et al., 2006).

The SJA trials produced an average increase of 10.1 cm (22.7%) in jump height and 0.27 m/s (10.98%) in vertical velocity at take-off, similar to previous findings of 8.2 cm and 0.31 m/s (Feltner et al., 1999), 7.8 cm and 0.26 m/s (Feltner et al., 2004), and finally 8.6 cm and 0.23 m/s (Lees et al., 2004). Later work by Hara et al. (2008) examined the segmental transfer between the upper and lower-extremities, measuring SJ and CMJ with (SJA and CMJA) and without (SJNA and CMJNA) an arm-swing. The effect of arm-swing contribution (CMJNA compared to CMJA) typically showed a percentage increase of 17.6% in jump height and 6.9% in vertical velocity at take-off, Conversely, a comparison of lower-extremity countermovement contribution (CMJA compared to SJA) demonstrated a smaller percentage increase of 9.2% in jump height and 4.5% in vertical velocity at take-off. In comparison to lower-extremity countermovement, the arm-swing appears to be the primary contributor to increasing in jump height and vertical velocity. Notably, this is further depicted when comparing jumps that had no lower-extremity countermovement and an arm-swing (SJA), to jumps that had a lower-extremity countermovement but no arm-swing (CMJNA), demonstrating an increase of 7.71 % and 2.29 % during SJA for jump height and vertical velocity at take-off, respectively.

Hara et al. (2008) suggest the increase in jump height during the arm-swing conditions (CMJA and SJA) is caused by the increase in rotation of the upper-extremities, and the subsequent positive effect on the lower-extremities. Hara et al. (2006) indicated SJA jump height and vertical velocity was primarily created by the effect of the arm-swing on the trunk and hip, increasing hip work by 18% in comparison to the SJNA condition. Moreover, this increase was created by utilising greater trunk inclination during SJA, effectively increasing the load on the trunk and hip. However, these findings should be treated with caution as a full arm-swing was not utilised during the SJA condition. The arm-swing start position (Figure 2.8) during SJA was at the point of maximum shoulder hyper-extension, indicating no arm back-swing phase (arm countermovement) being utilised. If the trunk is actively positioned by the arms during the arm back-swing phase, and increased in respect to arm-swing velocity, then using no arm back-swing phase may have reduced the increase increment in jump height for the SJA condition.

In a full body kinematic chain, the proximal segment to the trunk is the upper-arm segment, rotating at the shoulder joint to create an opposing force on the trunk segment, therefore, the faster the arm-swing during SJA, the faster the rate of trunk inclination. Hara et al. (2008) argued that increasing arm-swing rotation (proximal) would effectively increase trunk rotation (distal), and the increase in joint rotation would progress distally, suggesting a pattern of proximal to distal joint rotations initiated by the arm-swing. This demonstrates similar findings to Vanrenterghem et al. (2008) who noted increased trunk rotation (distal) leading to an increase in the rate and magnitude of trunk flexion, and a consequent increase in power at the hip joint (+37%). Interestingly, the initial arm-swing rotation (proximal) increasing the rate of hip flexion is created by shoulder hyper-extension (arm-swing countermovement), suggesting the back-swing of the arms as a vital component in increasing the rate and magnitude of trunk flexion. This suggests evidence of proximal to distal loading, meaning the proximal segments initially rotate in the opposing direction to create increased pre-stretch in the agonist musculature during joint flexion. Therefore, arm-swing rotation acts on the lower-extremities in two ways, firstly flexing the trunk and legs during lower-extremity countermovement (arm back-swing), and secondly extending the trunk and legs during their propulsion (arm down-swing and up-swing). This offers evidence of an arm propulsive phase, and develops further justification for the examination of the arm-swing mechanics prior to the leg propulsive phase.

Proximal to distal loading during CMJA has been examined in the lower-extremities, but with no reference to arm-swing and trunk contribution. Moran et al. (2007) suggest an increase in eccentric loading within the hip, knee and ankle extensor muscles during a countermovement, subsequently increases concentric performance. This is demonstrated by the increase in VGRF and jump height, when comparing drop jump (DJ) performance (increased eccentric load) to CMJ performance. However, an increase in eccentric load (hip, knee and ankle extensor muscles) could also occur by utilising the mechanics of the arm-swing. Hara et al. (2008) showed increased arm-swing rotation effectively increasing trunk rotation, and a subsequent increase in the rate and magnitude of trunk flexion. The increase in rate of trunk flexion during segment rotation (proximal), and subsequent knee and ankle flexion (distal), will effectively increase the rate of lower-extremity eccentric loading, demonstrating a link between upper-extremity segment rotation and lower-extremity eccentric loading. Consequently, to increase lower extremity eccentric loading in the hip, knee and ankle extensor muscles, the rate of trunk flexion should be maximal, and developed by increasing arm-swing velocity. The lower-extremity loading phase occurs during the back-swing and down-swing phases of the arm-swing; therefore, peak arm-swing rotation should occur during the latter of these two phases (down-swing). This further suggests the need for an investigation into the arm-swing countermovement (back-swing) and initial arm-swing propulsion (down-swing) phases.

The arm-swing provides a positive effect on vertical jump performance (Feltner et al., 1999; Lees et al., 2004; Lees et al., 2006; Hara et al., 2006; Gerodimos et al., 2008; Hara et al., 2008); however, no consensus amongst researchers has been reached regarding how the positive effect is achieved. The phases of the arm-swing need to be reconsidered to ensure none are being disregarded from analyses, as previous studies have often focused on the arm-swing effect within the lower-body movement, and not the full arm-swing (Feltner et al., 1999; Hara et al., 2006). Furthermore, no researchers have examined the countermovement for the arm-swing, which when related to the lower-extremity countermovement, is reported as being an integral system for improving training and performance (Bobbert et al., 1996; & Gerodimos et al., 2008) Therefore, the same mechanisms may be present within the upper-extremities. It is clear that key arm-swing variables have not been scrutinised adequately and warrant further investigation.

2.4 Loading of the SSC during countermovement’s

Eccentric loading in the lower-extremities during jumping

The countermovement in the lower-extremities has been examined under varied eccentric loads (Bosco & Komi, 1979; Walsh, Arampatzis, Schade & Bruggemann, 2004; Ishikawa, Niemela & Komi, 2005; Moran et al., 2007; McBride et al., 2008) and manipulated by changing jump type (SJ, CMJ, and DJ), active range of motion (70° and 90°), loading mass (10 to 160 kg) and eccentric load drop height (20 to 90 cm). Moran et al. (2007) noted the increase in concentric performance in the lower-extremities during a CMJ was sensitive to the eccentric pre-loading phase. This has been demonstrated by comparing SJ, CMJ and jumps with increased drop height (DJ), as well as comparing DJ from various drop heights (DJ-12 to DJ-90). The results indicate that peak concentric force was dependent on peak eccentric load, as identified within the DJ condition (DJ ≥ CMJ ≥ SJ). In respect to jump condition (SJ, CMJ & DJ), comparative eccentric load studies (Table 2.1) demonstrate that jumps with the highest eccentric load (DJ ≥ CMJ ≥ SJ) produce the greatest increase in jump height, VGRF and the peak joint moments. Furthermore, an increase in DJ drop height appears to increase jump height when dropping from a mid value height (DJ 12-40), yet not consistent for the highest drop heights (DJ 60 -90).

Table 2.1 Optimal eccentric load condition during squat jumps (SJ), countermovement jumps (CMJ) and varied drop height drop jumps (DJ).

Research	Jump type (Eccentric load)	Peak condition
Bobbert et al. (1987a)	CMJ / DJ-20	DJ-20
Bobbert et al. (1987b)	DJ-20, 40, 60	DJ-20
Lees et al. (1994)	CMJ / DJ-12, 24, 36, 46, 58, 68	DJ-12
Voigt et al. (1995)	DJ-30, 60, 90	DJ-30
Walsh et al. (2004)	DJ-20, 40, 60	DJ-40
Ishikawa et al. (2005)	DJ-peak, Peak -10 (low)**, peak +10(high) ***	DJ-peak
Moran et al. (2007)	SJ/ CMJ / DJ-30	DJ-30
McBride et al. (2008)	CMJ / DJ-peak*	DJ-peak
Earp et al. (2010)	SJ/ CMJ / DJ-peak	DJ-peak

* DJ-peak: A dropping height equal to Peak CMJ height

** Peak -10 cm Low: A dropping height 10 cm less than the peak drop height

*** Peak +10 cm High: A dropping height 10 cm greater than the peak drop height

Collectively, the peak eccentric load condition for increasing jump height was the DJ, ranging from DJ-12 to DJ-40 in comparative studies with more than one DJ height. Conversely, the study demonstrating the largest increase in eccentric load DJ-90 showed a decrease in jump height when compared to DJ-30 (Voigt et al., 1995), demonstrating similar findings to other studies examining the optimal eccentric load in respect to jump height; DJ-20 = DJ-60 (Bobbert et al., 1987b), DJ-12 ≥ DJ-68 (Lees et al., 1994) and DJ-40 ≥ DJ-60 (Walsh et al., 2004).

Bobbert et al. (1987b) examined six physically fit males who each performed two maximal DJ from 20 cm (DJ-20), 40 cm (DJ-40) and 60 cm (DJ-60) and kinematic and kinetic data were collated using video analysis from a single high-speed camera (100 Hz) and force analysis from a single force platform (500 Hz). Bobbert et al. (1987b) observed an increase in VGRF in respect to an increase in DJ height (DJ-60 ≥ DJ-40 ≥ DJ-20); however, no significant increase in jump height was found during DJ-60. Bobbert et al. (1987b) suggested jumps with high eccentric loads cannot facilitate the increase in VGRF into an increase in jump height, primarily due to the ankles inability to maintain joint stiffness during ankle dorsi-flexion at the bottom of the countermovement. Effectively, the heel is forced down to the ground during DJ-60, indicating that any increase in concentric performance following the eccentric pre-stretch during DJ-60, is lost during a large eccentric braking movement of the plantar flexor muscles of the ankle (gastrocnemius). This indicates that even though the SSC at the ankle joint contributes towards overall jump height, its contribution is compromised during high-level eccentric loads that are observed when muscles are stretched rapidly whilst acting as brake to the body’s COM from large drop heights. This showed conflicting results to previous studies that had demonstrated a positive relationship between the increase in DJ drop height and jump height, even at the greatest drop heights (Asmussen & Bonde-Petersen, 1974; Komi & Bosco, 1978), and may be explained by the type of jump technique utilised in each of the studies.

Early work by Asmussen et al. (1974) and Komi et al. (1978) had participant’s perform CMJ from different heights, with their normal choice of CMJ technique. This allowed each participant to self-regulate the amount of joint flexion used during the eccentric phase, implying that during the DJ from higher heights (DJ-peak), a lower squat depth with more joint flexion could be utilised (increased eccentric load). This presents a method in which each participant could increase their eccentric load, therefore increase their concentric performance similar to the DJ from lower heights. For example, a DJ from 60 cm could utilise a 120° squat, whereas a DJ from 20 cm might only use a 70° squat, suggesting that the DJ60 cm would increase their eccentric load (increased squat depth) more than DJ20 cm.

Conversely, the later work by Bobbert et al. (1987b) utilised a DJ technique that used minimal joint flexion during all DJ conditions (20, 40 and 60 cm start heights), where participants performed a rapid bounce style DJ with minimal joint flexion and eccentric loading, even during the DJ-60 condition. VGRF would increase in response to an increase in DJ height irrespective of jump technique, however, Bobbert et al. (1987b) showed that a DJ-peak had a negative impact upon jump height due to changed kinematics in the ankle (lowered to the floor), which led to a decrease in concentric performance. In contrast, the research by Komi et al. (1978) demonstrated DJ-peak coupled with an increased squat depth as a possible method to avoiding change in ankle kinematics, as a lower squat could facilitate the use of the larger knee flexors (quadriceps) instead of the smaller ankle plantar flexors (gastrocnemius). Nevertheless, this method should be criticised as the amount of eccentric load has not been controlled, suggesting that DJ-peak performed with an increased squat depth would lead to a greater jump height than DJ-peak performed with a controlled squat depth.

The different styles of jump technique used by previous studies to examine the optimal DJ heights in jumping were criticised by Moran et al. (2007). They suggested that variables such as active range of motion and DJ drop height were often not controlled during different jump conditions, yet these key contributing factors to the mechanics of jumping could help explain how eccentric loading increases jump performance, and therefore required further exploration. Participants performed SJ, CMJ & DJ-30 (small (SJ), medium (CMJ) and large (DJ-30) eccentric loads) each with 70° & 90° of knee flexion (small (70°) and medium (90°) active range of motion). An increase in both jump height and joint moments were observed when utilising greater eccentric loads. Furthermore, when utilising a greater active range of motion at the knee (90° c.f. 70°), Moran et al. (2007) found an inverse relationship between eccentric loading and active range of motion, showing the optimal eccentric load condition for achieving maximum jump height was a large eccentric load (DJ-30) coupled with a small active range of motion at the knee (70°). However, jumps with a large eccentric load coupled with a medium range of motion at the knee (90°) showed a decrease in jump height, suggesting that the improvement in jump height observed during large eccentric loads can only be facilitated when athletes are able to maintain joint stiffness and increase joint flexion, which ultimately leads to any improvements in joint kinematics being reduced or lost.

Interestingly, a similar inverse relationship showed an opposite trend for jumps with small eccentric loads (CMJ), suggesting that if one variable required a high range value, it required the other variable to be low, and vice versa. This was shown best by the decrease in jump height during DJ-30 coupled with a medium range of motion at the knee (90°), as once the eccentric load was reduced, the lower-extremities now required an increase in range of motion at the knee to gain the best possible jump height. In explanation of the findings by Moran et al. (2007), It may be suggested that during jumps with a large increase in eccentric load (peak-DJ drop height), the lower-extremity extensor muscles are required to react to the increased pre-stretch by initiating a faster opposing concentric contraction, especially when compared to jumps demonstrating only minimal muscle pre-stretch, such as those observed in smaller DJ drop heights or CMJ.

This requirement may be due to the leg muscles actively utilising the SSC, stretch reflexes and the reutilisation of elastic energy (Bobbert et al. 1996; Komi et al., 1997; Lees et al., 2004), all of which have been demonstrated to be at the detriment of increased muscle pre-stretch and a rapid transition between eccentric and concentric contractions. Furthermore, during jumps with a reduced eccentric load (CMJ), the same use of the SSC, stretch reflexes and reutilisation of elastic energy may not be available due to the reduction in muscle pre-stretch, therefore, the leg muscles adopt the use of an increased amount of active range of motion at the knee in attempt to increase eccentric muscle activity prior to the transition into concentric performance. Nonetheless, in all jump variations, the transition phase seems to be an important consideration.

Moran et al. (2007) alluded to the transition phase as a key contributing factor in eccentric loading, responsible for the differences in jump height when comparing jumps with different active range of motions or eccentric loads. The transition between the eccentric and concentric contractions, is known as eccentric concentric coupling (E-C coupling), referring to the isometric contraction period occurring between coupled eccentric and concentric contractions. Table 2.2 shows that irrespective of joint location (hip, knee and ankle) or eccentric load type (CMJ and DJ-30), the use of 70° active range of motion at the knee decreases transition time. When active range of motion conditions are cross examined, that is, CMJ 70° compared to DJ-30 70° and CMJ 90° compared to DJ-30 90°, the greater eccentric load jumps (DJ-30) demonstrate a shorter transition phase. Therefore, the fastest transition period was demonstrated by the DJ-30 with 70° active range of motion, which interestingly is the same condition that produced the greatest jump height.

Table 2.2 Mean and standard deviation (±) transition times (ms) during countermovement jumps and drop jumps from 30 cm with varied active range of motion (70° & 90°) (Moran et al., 2007).

Jump	CMJ	CMJ	DJ-30	DJ-30
Knee angle	70°	90°	70°	90°
Hip (ms)	36 ± 14	56 ± 18	22 ± 7	41 ± 14
Knee (ms)	23 ± 14	64 ± 46	17 ± 17	55 ± 46
Ankle (ms)	248 ± 75	596 ± 161	63 ± 52	199 ± 94

Once again, the evidence suggests that increased eccentric load during vertical jumps is a vital consideration for achieving jump height, and the transition phase appears to have the greatest impact upon which eccentric load is optimal to use, especially when performing DJ from varied drop heights. Furthermore, it may be suggested that jump height would increase further if coupled with an even faster transition time, and this could demonstrate why muscle adaptations such as neuromuscular stiffness develop, as the muscles attempt to facilitate a better response to increased muscle pre-stretch (McBride et al., 2008).

The importance of E-C coupling during DJ performance is typified by the balance between high eccentric loading and the body’s ability to convert the associated positive effects from eccentric loading into concentric performance. According to Ingen-Schenau et al. (1997a) if the transition is rapid, the role of the stretch reflex system would play a vital role. Komi et al. (1997) argued that as DJ height increases from 20 cm to 60 cm, pre-stretch in the muscle increases in a linear relationship with jump height. Conversely, as DJ height increased from 60 to 80 cm, the increase in jump height starts to decline rapidly suggesting there is an optimal level to eccentric loading in a muscle, and once reached, jump height will decline in a curvilinear trend (Komi et al., 1997; Moran et al., 2007).

The decline in jump height observed under high eccentric loading might be because of the inhibitory mechanism of the stretch receptors within the muscle-tendon junction (Komi & Gollhofer, 1997). This suggests an optimal balance between increased eccentric loading and utilisation of the muscles stretch receptors (Golgi tendon organ, GTO) and the stretch reflex system (Schmidtbleicher, Gollhofer & Frick, 1988; Gollhofer, Stronjnik, Rapp & Schweizer, 1992). Moreover, the increased eccentric load coupled with increased active range of motion at the knee (DJ-30 90°) demonstrated by Moran et al. (2007) may have loaded the muscles too much to utilise the stretch reflex system, and increased muscle pre-stretch (90°) may have initiated an increase in GTO activation. A rapid E-C coupling appears to be the main contributing factor to varied eccentric loading, which has also been shown to be vital in the utilisation of the stretch-shortening cycle (Komi, 2000), increased muscle potentiation (Bobbert, 1990) the stretch reflex system (Komi et al., 1997) and transfer of kinetic energy as demonstrated in Figure 2.9 (Lees et al., 2004).

The optimal range for eccentric loading is demonstrated upon closer examination of the balance between the required eccentric load for optimal elastic energy utilisation and inhibition from the GTO (Figure 2.9). Comparative eccentric load studies in jumping have shown elastic energy increasing under greater eccentric loads (DJ) when compared to jumps using less eccentric load (CMJ) (Lees et al., 2004; Lees et al., 2006), indicating the greater the increase in eccentric load the greater the gain in jump height.

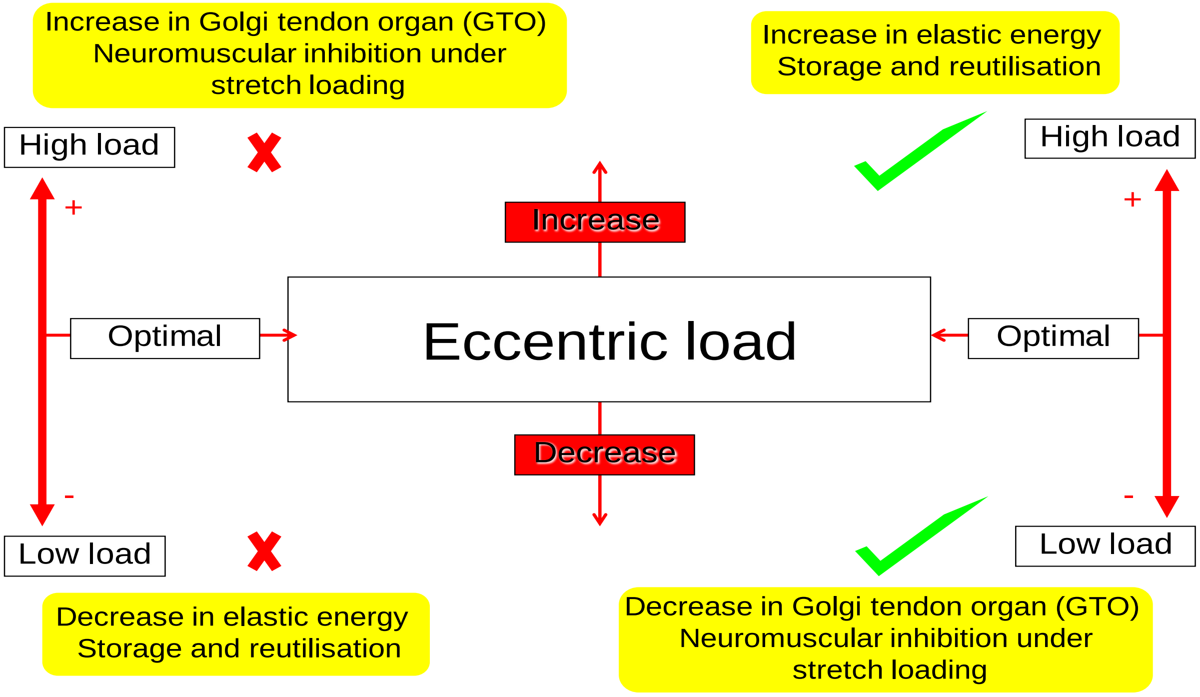


Figure 2.9 Optimal eccentric load conditions during the increase and decrease in Golgi tendon organ activation, and utilisation of stored elastic energy.

However, this is not always true, with some studies showing a decrease in jump height during high eccentric loads (Lees et al., 1994; Voigt et al., 1995). Conversely, GTO activation increases during greater magnitudes of eccentric loading, causing an inhibitory effect upon the pre-stretched muscle and ultimately leading to a decrease in the subsequent concentric contraction (Schmidtbleicher et al., 1988; Komi et al., 1997; Walsh & Wilson, 1997). The large magnitude in muscle stretch during the DJ-30 90°, yet attenuated in DJ-30 70° could be demonstrating the negative relationship between increased elastic energy utilisation and increased GTO activation (Moran et al., 2007). Furthermore, the optimal conditions for the balance between these mechanisms are yet to be identified, and warrant further investigation.

The optimal conditions required for participants to increase jump height under varied eccentric load are individualistic, as the balance point between an extreme high eccentric load (high GTO inhibition) and an extreme low eccentric load (low elastic energy utilisation) will vary according to each individuals muscular characteristics. Ishikawa et al. (2005) attempted to compensate for the observed changes in individuals by using a DJ height corresponding to the participant's peak CMJ height (DJ-peak). A high and low condition representative of a height 10 cm above and 10 cm below this optimal value was identified. Eleven male and female participants performed three maximal jumps per jump condition, and kinematic and kinetic variables were recorded using high speed video analysis (200 Hz), simultaneous electromyography and force analysis (500 Hz), and Ultrasonography. Peak CMJ height and transition time followed a parabolic trend, demonstrating a peak during the middle range condition (DJ-peak) and marked decreases in both the low and high conditions, indicating an optimal condition somewhere in the middle as shown in previous studies (Lees et al., 1994; Voigt et al., 1995; Moran et al., 2007).

The optimal condition in the lower-extremities for eccentric loading during vertical jumping appears to be a high eccentric load with small range of motion. However, if either eccentric load or active range of motion increase or decrease too greatly, a decrease in jump height can be observed (Moran et al., 2007). The main reason for this decrease is down to the relationship between the increased utilisation of the SSC, stretch reflex system and the reutilisation of elastic energy, and the decrease in the use of the inhibitory mechanism of the Golgi tendon organ (GTO). If the influence of all these mechanisms can be balanced, as shown in the study by Ishikawa et al. (2005), then jump height will occur in the middle of a parabolic trend between eccentric load and active range of motion. However, all these mechanisms require a rapid transition time between the eccentric and concentric contractions, and faster transition times require further exploration. Furthermore, similar muscle loading principles may be utilised by the upper-extremities, and with respect to vertical jumping, this has not been examined and warrants further investigation.

Variable eccentric loading in the upper-extremities during weighted exercises

The increase in eccentric load during upper-extremity movements has often been examined in respect exercises using increased weight during eccentric muscle contractions. Doan et al. (2002) demonstrated experienced weight lifters increased the amount of weight lifted during a concentric one repetition maximum (1RM) barbell bench presses when the load during the preceding eccentric contraction was 105% of concentric 1 RM. Doan et al. (2002) suggested that the increase in weight lifted in the subsequent concentric contraction resulted from an increase in the use of the SSC. Newton et al. (1997) examined neuromuscular performance during upper body ballistic bench throws with variable eccentric loads. Seventeen experienced male weight lifters performed three concentric only and three SSC bench throws of a weighted bar with seven different percentage loads (15, 30, 45, 60, 75 & 90 %) of their 1RM, during which kinematic and kinetic variables were assessed using synchronised force analysis from a single force platform (876 Hz) and electromyography for the pectoralis major, anterior deltoid and triceps brachii (876 Hz). As the bar load increased peak throw height decreased while peak force linearly increased for both the concentric only and SSC throws.

This suggests that an increase in eccentric load in the upper-extremities has a negative impact upon concentric performance. Conversely, research that examined loading in the lower-extremities during vertical jumping showed that as eccentric load increased, concentric performance increased, that is, jump height was greater when performed with a high eccentric load (Moran et al., 2007; Lees et al., 1994). However, eccentric loading in the study by Newton et al. (1997) was manipulated by increasing weight in the bar, whereas Moran et al. (2007) changed load by increasing DJ drop height (increased speed of the eccentric load/muscle stretch) and the amount of active range of motion used at the knee (magnitude of the eccentric load). Manipulating the amount of eccentric load by using only one method may have limited the findings of Newton et al. (1997), reflected by no increase in peak throw height, as Moran et al. (2007) established there was more than one way to increase eccentric loads. These included the increased rate of the eccentric load and increased magnitude of the eccentric load, and may have been a recommended addition to the study by Newton et al. (1997), achieved by dropping a fixed load from different heights and also eccentrically lowering the bar to different heights, which may have developed better variation in muscle pre-stretch and overall eccentric loading (Moran et al., 2007).

Newton et al. (1997) aimed to identify the use of the upper body SSC by comparing ballistic bench throws with and without a preceding eccentric movement (concentric movement only). The use of a preceding eccentric movement significantly increased the average concentric velocity, average force and peak force, and a decrease in concentric movement time for all eccentric load conditions, however, peak throw height remained constant throughout. Nonetheless, the bench throws performed with the preceding eccentric movement showed that the use of the SSC was favourable for increasing peak concentric velocity and force. This was confirmed by a significantly greater EMG activity in the pectoralis major and triceps brachii over the first 100 ms for the bench throws performed with a preceding movement, indicating that the eccentric contraction prior to the concentric performance initiated the use of the SSC. This offers further evidence that muscle pre-stretch increases the active state of the muscles prior to a concentric contraction (Bobbert et al. 2005), which will increase the opportunity for utilisation of elastic energy (Lees et al., 2004).

The use of the SSC during ballistic bench throws should have increased peak throw height over the concentric only throws; however, this would be dependent upon the participant's ability to effectively use the SSC during this type of exercise (Komi, 2000; Turner & Jeffreys, 2010). As alluded to previously, the participant's previous weight lifting experience may have been only lifting weights in a none-ballistic manner, suggesting an SSC movement under heavy eccentric loading as unfavourable compared to the concentric only condition. This would affect the participant's ability to utilise the increased eccentric load during the subsequent concentric movement (Newton et al., 1997), and may be affected by the inability to use the associated SSC mechanisms such as utilisation of elastic energy (Lees et al., 2004), E-C coupling and the stretch reflex system (Komi et al., 1997). Furthermore, the bench throws performed in the concentric only condition had a longer time period available to produce force (+ 264 ms), therefore, the faster and more explosive movement observed in the SSC condition involved a shorter concentric action, therefore reducing the time available to produce concentric force, and this may have led to the decline in the overall throw height achieved.

Indeed, the transition between the preceding eccentric phase and the ballistic concentric movement would need to be rapid, which again may be something heavy weight lifters are less able to perform than athletes accustomed to training using ballistic exercises. Work by Miyaguchi & Demura (2008) examined upper body eccentric loading during elbow flexion with and without a preceding eccentric movement, showing a significant increase in initial concentric arm velocity (+ 0.18 $m.s^{-1}$) and peak arm swing velocity (+ 0.04 $m.s^{-1}$) and overall increase in muscle strength (+ 17%). This was similar to previous findings for similar studies comparing upper body movements with and without a preceding eccentric movement (Fukashiro, 1997; Benoit & Dowling, 2006), providing more evidence that upper-extremity exercises that are preceded by a countermovement can utilise the SSC. Interestingly, during vertical jumping the upper-extremities utilise an arm-swing that consists of both an eccentric and concentric phase, however, the use of the SSC during this movement has never been previously examined and warrants further investigation.

Later work by Miyamoto et al. (2010) examined elbow extension with (SSC) and without a countermovement, demonstrating a significant increase in joint power during the SSC condition. Furthermore, elbow extension was measured under variable load (0, 2.5, 5.0, 7.5, 10.0, 12.5 & 15.0 kg) showing optimal load conditions for joint power of 7.5 kg in the SSC condition and 5.0 kg in the no countermovement condition. The change in optimal load between the SSC and no countermovement conditions suggests that the use of a preceding eccentric movement creates advantageous changes in the body's musculature, which is evidenced by the increase in optimal load during the SSC condition of 2.5 kg. The authors suggested the increase in optimal load during the SSC condition was achieved by the effective reutilisation of elastic energy developed by the preceding eccentric movement, suggesting if this was increased further, a greater increase would be observed, yet during the loads of 10 kg or higher, a decrease in joint torque occurred. This could be explained by the increase in cross bridge head detachment under greater load (muscle potentiation) coupled with the inhibition from the GTO in response to high level pre-stretch in the muscle as previously discussed (Schmidtbleicher et al., 1988; Gollhofer et al., 1992; Flitney et al., 1978; Ishii Et al., 1997), and offers further evidence of an optimal load in SSC movements that occurs on average in the middle of a parabolic curve during eccentric loading.

The average optimal load for elbow extension (7.5 kg) during an SSC movement is situated once again in the middle of a parabolic curve, demonstrating eccentric loads that are too high or too low negatively impacting upon elbow extension (Miyamoto et al., 2010), and showing further evidence of the balance between the positive increase in reutilisation of elastic energy and the negative increase in GTO activation (Ishikawa et al., 2005). Conversely, work by

Moran et al. (2007) noted that concentric performance when preceded by an increased eccentric load was affected by other load variables such as AROM of the joint, and the rate and magnitude of muscle pre-stretch during the eccentric movement. Indeed, during normal sporting actions such as jumping and throwing, the eccentric movement during SSC type movements is affected by many variables other than just increased load, such as variable start position, change in active range of motion, rate and magnitude of load, transition time and the force velocity relationship of the muscle (Lees et al., 1994; Voigt et al., 1995; Moran et al., 2007; McBride et al., 2008), therefore, the optimal conditions in upper-extremity movement needs to be further explored. Moreover, this has never been examined for the arm-swing during vertical jumping even though it demonstrates a countermovement, and could be manipulated by increasing the start position, active range of motion utilised, speed of swing and increased weight. The identification of the optimal conditions for countermovement's to maximally improve concentric performance is a vital consideration in determining how the SSC works under varied conditions, and arguably would benefit the future enhancement of these SSC movements.

2.5 Plyometric exercise used to enhance stretch-shortening cycle movements

Lower-extremity plyometric exercises used to improve vertical jumping

Plyometric exercises are a type of exercise that when performed maximally, utilise the SSC, stretch reflex and elastic energy systems within the specific muscle targeted (Chu & Plummer, 1984; Chu, 1993; Luebbers et al., 2003; Marques, Marinho & Van Der Tillaar, 2010). Plyometrics enhance the force and speed of muscular contraction (Chu, 1983; Chu & Plummer, 1984; Holcomb, Lander, Rutland & Wilson, 1996a; Holcomb, Lander, Rutland & Wilson, 1996b; Luebbers et al., 2003; Miller, Herniman, Ricard, Cheatham & Michael, 2006) and it is well established that plyometric exercises help athletes maximise their ability to utilise the SSC (Gehri, Ricard, Kleiner & Kirkendall, 1998; Toumi, Best, Martin, Guyer &

Poumarat, 2004; Lephart et al., 2005) According to Chu (1983), the faster a muscle is stretched eccentrically (lengthening), the more powerful it will contract concentrically (shortening), providing greater force of contraction during the propulsive phase. Indeed, plyometrics have been used successfully to enhance performance in soccer (Ronnestad, Kvamme, Sunde & Raastad, 2008; Thomas, French & Hayes, 2009; Rubley et al., 2011), tennis (Salonikidis & Zafeiridis, 2008; Suthakar, Annida, Kanaga & Senthil, 2009), golf (Fletcher & Hartwell, 2004), baseball (Ellenbecker, Roetert, Davies & Brown, 2002) and throwing (Marques et al., 2010).

Plyometrics are commonly associated with improved vertical jump performance and are widely used for increasing jump height (Innocenti, Facchielli, Torti & Verza, 2006; Moore, Weiss, Schilling, Fry & Li, 2007; Markovic, 2007). Indeed, in a recent meta-analysis, it was proposed that plyometric exercise resulted in an average increase of 7% in vertical jump performance after training (Villarreal, Lellis, Kraemer & Izquierdo, 2009b). However, some studies have indicated that plyometric training has no effect (Millar, Berry & Bullard, 2002; Turner, Owings & Schwane, 2003; Herrero, Izquierdo & Maffiuletti, 2006) or a negative impact (Luebbers et al., 2003) on vertical jump performance.

Currently, most research in this area has focused on the lower-extremities contribution to vertical jumping and the mechanisms that explain improved jump performance (Ronnestad et al., 2008; Ebben, Simenz & Jensen, 2008; Villarreal, Gonzalez-Badillo, & Izquierdo, 2009a; Arabatzi et al., 2010). These plyometric programmes are dominated by lower-extremity exercises primarily aimed at increasing speed and strength in the lower body musculature, and overall jump height (Fatouros et al., 2000; Impellizzeri et al., 2008; Marques et al., 2008; Arabatzi et al., 2010; Khlifa et al., 2010; King & Cipriani, 2010).

Early work examining vertical jump responses to plyometric interventions attempted to identify the optimal conditions for increasing vertical jump height, comparing CMJ to DJ performance as well as examining the optimal drop heights for DJ (Bosco & Komi, 1979; Bobbert et al., 1987b; Lees et al., 1994; Voigt et al., 1995). Subsequent studies diverted their focus to the type of training utilised, examining plyometric interventions combined with resistance weight programmes (Holcomb et al., 1996b; Fatouros et al., 2000, Maffiuletti et al., 2002; Siegler, Gaskill & Ruby, 2003; Khlifa et al., 2010; Arabatzi et al., 2010), variable intensity (Jensen & Ebben, 2007; Ebben et al., 2008; Sankey, Jones & Bmapouras, 2008), variable frequency (Villarreal et al., 2009a), electromyostimulation (Herrero, Izquierdo, Maffiuletti & Garcia-Lopez, 2005) and variable jump type (Adams, O'Shea, O'Shea & Climstein, 1992; Holcomb et al., 1996a; Holcomb et al., 1996b; King & Cipriani, 2010).

A meta-analysis examining fifty-six plyometric studies revealed that high-intensity plyometrics coupled with electromyostimulation or resistance weight and a combination of DJ, CMJ and SJ, would be the optimal combination of plyometric exercises for maximally increasing jump height (Villarreal et al., 2009b). However, early work by Chu (1998) argued that the success of any plyometric exercise is achieved through the careful manipulation of four variables (intensity, frequency, volume and recovery), and that specificity of adapting the exercise to suit the specific requirements of each individual (athlete or sport) would ensure these four variables could be utilised to their maximal potential. Chu (1998) described plyometric intensity as dependent on the type of exercise, indicating that exercises could be ranked on an intensity scale, suggesting exercises are ranked as *low-intensity* exercise (standing jump) or *high-intensity* exercise (depth jump) depending upon the physical demands of each individual exercise. However, low and high-intensity exercises can both be performed with low and high intensity. Therefore, if all exercises are performed maximally during each repetition, the intensity of an exercise can now be graded by the physical demand of that exercise. Importantly, maximal intensity exercises will need to be carefully planned for the amount of repetitions and sets that are performed (volume), and the amount of times these sets are performed (frequency), as plyometric programmes that consist of both high volume and high frequency plyometric exercises could have a negative impact upon training, as athletes could find it hard to adhere to high volume and high frequency maximal intensity exercises.

The intensity principle proposed by Chu (1998) links to the mechanisms of the SSC, as exercises that are performed maximally will utilise greater increased pre-stretch during the eccentric muscle contraction phase, indicating the ideal conditions eccentric loading (Moran et al., 2007), increasing the utilisation of elastic energy (Lees et al., 2004), optimal use of the stretch reflex system (Komi & Gollhofer, 1997), and furthermore, the active state in the muscles will demonstrate a greater increase during maximal eccentric loading, therefore leading to increased concentric muscle performance (Bobbert et al., 1999). It could be argued that exercises performed sub maximally may not initiate the full use of the SSC system and associated mechanisms, therefore, may have a negative impact upon training. This offers further justification that the amount of volume and frequency of plyometric exercise should be minimal during exercise programmes, therefore allowing athletes the optimal chance to perform each exercise maximally. Later work by Villarreal, Gonzalez-Badillo and Izquierdo (2008) indicated that maximising an athlete’s response to plyometric training would require optimal volume and frequency of plyometric exercise. While inconclusive, a summary of the duration, frequency and volume of various plyometric training interventions, and their impact on jump height are provided in Table 2.3.

Table 2.3 Comparative studies for lower-extremity plyometric programmes

Study	Intervention duration (weeks)	Plyometric frequency*	Plyometric volume**	Vertical jump height gain (cm)
Cutch et al. (1983)	4	2	40	3.35
Hakkinen et al. (1985)	24	3	200	4.8
Adams et al. (1992)	6	2	75	3.81
Fowler et al. (1995)	3	4	50	4
Holcomb et al. (1996b)	8	3	72	4.7
Gehri et al. (1998)	12	2	32	2.79
Fatouros et al. (2000)	12	3	150	6
Diallo et al. (2001)	10	3	250	3.4
Maffiuletti et al. (2002)	4	3	50	5.2
Hunter et al. (2002)	10	2	60	3.7
Luebbers et al. (2003)	4	3	272	2.6
Turner et al. (2003)	6	3	70	2
Spurrs et al. (2003)	6	3	90	5
Villarreal et al. (2008) 1***	7	1	60	0.55
Villarreal et al. (2008) 2	7	2	60	4.6
Villarreal et al. (2008) 3	7	4	60	5.16

* Days training per week

** Number of jumps per session

*** Intervention type (1, 2 or 3)

The researchers developed no consensus on an optimal balance between plyometric volume, frequency and duration for maximally increasing jump height, as contrasting examples demonstrate similar jump height gains (3.35 and 3.4 cm) for opposing low frequency and low volume (2 and 40) and high frequency and high volume (3 and 250) plyometric programmes (Clutch et al., 1983 & Diallo et al., 2001, respectively). Furthermore, subject differences within each programme may have contributed to the small differences in trends. However, Villarreal et al. (2008) argued that it seemed justified that programmes that perform less jumps over a shorter time period and still develop similar increases in jump height to programmes performed with a greater number of jumps and over a longer time period, should therefore be advocated, as good gains in jump height achieved in faster time periods will be optimally perceived by athletes. This agrees with the intensity variable proposed by Chu (1998), suggesting that athletes performing less exercises would more likely achieve maximal intensity during each repetition of each exercise. Interestingly, this may offer insight to how plyometric exercises performed correctly (maximal intensity), can have a greater positive outcome (jump height) even if they have been performed less.

The optimal frequency for plyometric training was measured during a plyometric intervention consisting of identical volume and duration of plyometric exercises, with three different frequencies (1, 2 & 4 per week) (Villarreal et al., 2008). Results revealed that low frequency (1 per week) plyometrics resulted in a minimal gain in jump height (0.55 cm), and even though the high frequency resulted in a greater gain in jump height (4 per week, 5.16 cm) than the medium frequency (2 per week, 4.6 cm), Villarreal et al. (2008) argued that the gain was too small to warrant the use of an extra two sessions of plyometrics per week for seven weeks as beneficial. Furthermore, Villarreal et al. (2009b) suggest that increases in volume or frequency can lead to a decrease in the intensity of plyometric exercise, which would subsequently develop undesirable conditions for the optimal use of the SSC. This is further justification for using maximal effort high eccentric loading jumps such as the depth jump to optimally use the SSC and its associated mechanisms.

Two comparative meta-analysis studies found similar findings, also advocating high intensity (defined as maximal intensity depth jumps) exercise coupled with high eccentric load (DJ), and ballistic weighted exercises as optimal for increasing jump height (Markovic, 2007; Villarreal, Requena & Newton, 2010). According to Chu et al. (1984), the depth jump is the only true plyometric exercise that demonstrates the required explosive-reactive type of movement, and able utilise a rapid E-C coupling whilst under high eccentric loads. Bobbert et al. (1986) argued that studies demonstrating smaller responses to plyometric training often do so because the type of exercise chosen (SJ or CMJ) is inadequate in initiating responses from the SSC mechanisms, especially when compared to the high intensity depth jump. Furthermore, the role of the stretch reflex system and associated neural adaptations (neuromuscular stiffness) that occur in response to prolonged use of SSC movements, will arguably not occur during jumps with low eccentric loading rates (SJ & CMJ), indicating the depth jump as an optimal plyometric exercise (Bobbert, 1990; Young, Pryor & Wilson, 1995).

To increase the eccentric load in jumps used in plyometric interventions, early research advocated the use of resistance weight programmes (Fowler, Trzaskoma, Wit, Iskra & Lees, 1995; Hunter & Marshall, 2002). However, the findings from a meta-analysis revealed no difference in jump height gained when compared to plyometric programmes performed without added weight (Villarreal et al., 2009b). Furthermore, some plyometric studies reported a decrease in jump height when performed with extra weighted exercises (Potteiger et al., 1999; Spurrs, Murphy & Watsford, 2003), suggesting that the extra weight used during exercise actually increased the E-C coupling time, which in itself would have a negative impact on the utilisation of the SSC.

The varied responses to plyometric training suggests various neuromuscular mechanisms might explain improvements in jump height, including the use of stored elastic energy

(Sheppard, Newton & Mcguigan, 2007; Toumi et al., 2001; Lees et al., 2006), the contribution of reflex recruitment of additional motor units (Feltner et al., 2004; Harrison, Keane & Coglan, 2004; Myer, Ford, Brent & Hewett, 2006), joint coupling and coordination of muscle activation (Yamauchi & Ishii, 2007), increased rate coding (Jensen & Ebben, 2007; Markovic et al., 2007) and enhanced potentiation in the extensor muscles before ground contact (Young, Pryor & Wilson, 1995; Hennessy & Kilty, 2001). Previous investigators have achieved no consensus on which mechanism is primarily developed during plyometric programmes; however, they have acknowledged the possibility these mechanisms work in collaboration and are linked to the utilisation of the SSC.

Athletes in a wide range of sports have used plyometrics to enhance their specific sporting requirements (Ronnestad et al; 2008; Suthakar et al., 2009; Fletcher et al., 2004; Ellenbecker, et al., 2002), demonstrating similar responses to training as those demonstrated by athletes using plyometrics to enhance vertical jump performance. Indeed, to achieve sport-specific increases in performance, plyometrics have been tailored specifically to that sport (Villarreal et al., 2009b), for example a basketball player looking to develop an increase in lateral speed would use a plyometric intervention that uses frontal plane (medio-lateral) exercises, targeting the specific muscles used in that sport (King et al., 2010). When exercise specificity is related to vertical jumping, it demonstrates why so much attention is focused upon lower-extremity plyometric exercises, as leg contribution during vertical jumping is deemed the most important for contributing to jump height. However, the arm-swing also has a positive effect on vertical jump performance (Feltner et al., 2004), and the arm-swings' ability to improve jump performance following an upper-extremity plyometric programme has never been examined, and warrants further investigation.

Upper-extremity plyometric exercises used to improve sporting performance

In contrast to lower-extremity programmes, Swanik et al. (2002) noted that the majority of upper-extremity plyometric programmes had been advocated for use in rehabilitation, yet the plyometric exercises used within these upper-extremity plyometric programmes in shoulder rehabilitation studies were proving to be exercises that could help improve muscle performance. Chmielewski, Myer, Kauffman and Tillman (2006) stated that upper body plyometric exercises were primarily used in rehabilitation to promote stability in a joint after injury or a surgical procedure. Interestingly, the authors highlighted that upper-extremity plyometric used during sports rehabilitation were often used at low intensity, and to adopt these types of exercise for improving sports performance would only require the same exercises to increase to a higher intensity. This had been previously shown in upper-extremity plyometric interventions aimed at increasing performance in swimming (Swanik et al., 2002) and tennis (Treiber, Lott, Duncan, Slavens & Davis, 1998; Niederbracht, Shim, Sloniger, Paternostro-Bayles & Short, 2008); however, the exercises used in these upper-extremity plyometric interventions were aimed at increasing muscle strength and not sport-specific movement.

Movement-specific upper-extremity plyometric training was examined for its effect on baseball pitching (Carter, Kaminski, Douex-Jr, Knight & Richards, 2007). The authors found that plyometric shoulder exercises used for rehabilitation could be adapted to be used in a ballistic manner with high intensity to increase muscle performance. Twenty four male National League baseball players participated in an eight week UEP intervention, performing a set of six ballistic exercises twice a week, and strength and throwing velocity was collated using iso-kinetic dynamometry and a radar gun. The ballistic six exercise protocol was developed from exercises that had previously been used in the later stages of an upper-extremity plyometric rehabilitation programme for overhead throwing (Pretz, 2004) (Figure

2.10). The intervention comprised of; latex tubing shoulder external rotation, latex tubing 90° shoulder external rotation, 6-lb medicine ball overhead throws, 2-lb medicine ball side throws, 2-lb medicine ball deceleration baseball throws and a 2-lb medicine ball baseball pitch throw. The use of an upper-extremity plyometric intervention revealed increases of 0.89 $m.s^{-1}$ in throwing velocity and an increase in peak torque for both shoulder internal and external rotation.

Figure 2.10 The ballistic six upper-extremity plyometric exercises (Carter et al., 2007).

The effect of an upper extremity plyometric intervention was examined for its effect on throwing velocity in youth baseball players (Escamilla et al., 2010). Thirty four male youth baseball players participated in a short-term (four week) upper-extremity intervention, performing a set of seventeen elastic-band exercises coupled with a distance-based throwing protocol for seventy five minutes, three times a week. Throwing velocity was measured during maximal effort side arm throws by a radar gun, and results demonstrated an increase in throwing velocity of 1 $m.s^{-1}$ (2.2 mph), which were similar to previous findings of 0.89 $m.s^{-1}$ (2.0 mph) (Carter et al., 2007). The plyometric intervention used by Escamilla et al. (2010) was only four weeks long compared to the eight weeks adopted by Carter et al. (2007); However, the amount of exercises was more than double in duration, and the frequency of three times a week instead of twice as used by Carter et al. (2007). This may have resulted in similar positive gains in throwing velocity in a shorter time period. This advocates the use of plyometric programmes that utilise a high volume of upper-extremity plyometric exercises in a short-term intervention, and should be considered in future studies.

Even though the exercises examined in baseball were focused on throwing exercise (Carter et al., 2007; Escamilla et al., 2010), it may be possible to further adapt these exercises to other sports. Furthermore, the adaptation of sport-specific ballistic exercises could be developed for any upper body movement, suggesting the same principle could be utilised when developing exercises that would mimic the arm-swing during a countermovement jump (CMJ). The arm-swing during CMJ performance occurs in a single plane of motion (sagittal), indicating a loading phase depicted of shoulder hyper-extension and a subsequent propulsion phase of shoulder flexion (Lees et al., 2004, Gamble, 2010). This suggests shoulder movement characteristics that would utilise the muscles SSC (Knudson, 2003), and therefore be suitable for training using an upper-extremity plyometric intervention, and warrants further investigation.

Research examining the use of combined lower-extremity plyometric and upper-extremity plyometric for improving strength in both basketball and volleyball players have used a variation of upper-extremity plyometric exercises to improve strength (plyometric push ups, ballistic ball tosses and ballistic weight presses). Even though these exercises resulted in significant gains in upper and lower body strength post intervention, the exercises were not movement-specific and only targeted improvements in muscular strength and sporting technique (Adhikari & Kanchan, 2011). The authors failed to identify exercises that were movement-specific to either basketball or volleyball. Fortun et al. (1998) researched the use of an upper-extremity plyometric intervention for training overhead sport athletes (tennis, volleyball and throwing) utilising upper body plyometric exercises that were closely related to the characteristics of the arm-swing during vertical jumping. Thirty four men that were currently active in overhead sports participated twice a week in an eight week upper-extremity plyometric intervention, consisting of one exercise modality performed with varied weight, sets and repetitions. Various weighted balls were thrown at a Plyoback ball return system (Exertools, USA) that actively increased eccentric loading prior to the desired concentric movement (Figure 2.11).

Figure 2.11 Plyoback ball return system

The throws adopted by Fortun et al. (1998) occurred in the sagittal plane of motion with the ball being caught and thrown from above the head, and targeted down at the Plyoback ball return system. The transition from the eccentric loading phase to the throwing action using concentric movement was required to be as short as possible to ensure best utilisation of the SSC. To adapt this exercise to make it movement-specific to the arm-swing during vertical jumping, the action would remain in the sagittal plane of motion but the ball would be caught with the catching arm at the side of the body, therefore increasing eccentric loading as the ball forces the arm backwards creating an opposing resistance and mimicking the characteristics of the back-swing phase of the arm-swing. Furthermore, the arm-swing has been shown to have the same movement characteristics as those required for plyometric training (stretch-shortening cycle), and so the arm-swing should be a primary target for an upper body plyometric intervention (Lees et al., 2006). Research examining the use of upper-extremity plyometric exercises to improve sports performance is limited and not movement-specific. To date, an upper-extremity plyometric intervention designed for training the arm-swing during vertical jumping has not been examined and warrants further investigation.

2.6 Conclusions

The vertical jump has been extensively researched (Bobbert et al., 2005; Hara et al., 2006; McBride et al., 2008; Earp et al., 2010) with the main focus to date on the contribution made by the lower-extremity mechanics to overall vertical jump performance, and identifying mechanisms such as the lower-extremity countermovement as being vital for increasing jump height (Gerodimos et al., 2008). Furthermore, the suggested mechanisms proposed as responsible for the benefits provided by countermovement's during a concentric movement, including the active state development in muscles (Bobbert et al., 1996; Bobbert et al., 2005), potentiation of the contractile components (Binder-McCleod et al., 2002), the stretch reflex system (Komi & Gollhofer, 1997; Gerodimos et al., 2008), the stretch-shortening cycle (SSC) (McBride et al., 2008; Gerodimos et al., 2008) and the effective storage and utilisation of elastic energy (Bobbert et al., 1996; McBride et al., 2008), all play a role in explaining how the lower-extremities develop an increase in jump height. An important consideration is ascertaining which proposed mechanism contributes the largest amount towards vertical jump performance, as this has not been established, however a link between them appears to be the role of the stretch-shortening cycle (SSC) coupled with the effective storage and utilisation of elastic energy. This said, the lower-extremities are not the only contributing factor to vertical jump performance, as the use of an arm-swing has also been shown to contribute to achieving maximum vertical jump height (Feltner et al., 2004).

The arm-swing contribution to vertical jumping has been reported to increase jump height on average by 21.1%, yet despite being a larger contributor to jump height than the lower-extremity countermovement, the mechanisms responsible for how the arm-swing yields this increase are not fully understood. Indeed, the arm-swing is important for increasing ground reaction forces (Feltner et al., 1999; Feltner et al., 2004; Lees et al., 2006), joint torque (Feltner et al., 2004), joint ω (Feltner et al., 1999; Hara et al., 2006), transfer of energy (Lees et al., 2004), and for causing an overall change in segment positioning (Hara et al., 2006). However, the full extent to which the arm-swing yields these increases in key jump kinetics and kinematics is not fully understood, partly due to the early phases of arm-swing mechanics during a CMJ not being analysed (Feltner et al., 1999; Feltner et al., 2004). Nonetheless, what is clear regarding the arm-swing is how it has a positive effect upon hip extensor torques, lower extremity countermovement loading, and proximal to distal segment rotation (Feltner et al., 1999; Lees et al., 2004; Hara et al., 2006; Hara et al., 2008), and how it has the greatest effect upon these mechanisms during the early arm-swing phases of the jump. This suggests the arm-swing play a vital role throughout the whole of the vertical jump, and in respect of the aforementioned mechanisms, can help create further increases in the kinematics of other body segments, such as the trunk and lower-extremities. Interestingly, the early phases of the arm-swing, especially the arm-swing countermovement phase, have never been empirically examined, and this warrants further investigation.

If the arm-swing countermovement plays a vital role in overall jump kinematics, a method of training used to improve the mechanics of a countermovement is plyometrics, and plyometrics have been used in the lower-extremities, demonstrating positive increases in vertical jump height (Chu et al., 1984; Moran et al., 2007; Villarreal et al., 2009a; Villarreal et al., 2009b). However, plyometrics have not yet been examined for their suitability for training the upper-extremities, and how they could develop further increases in vertical jump performance. Upper body plyometric exercises have been advocated for use in rehabilitation (Swanik et al., 2002), especially for athletes that are currently post-injury or post-surgery and starting their road to recovery, yet research examining the use of upper-extremity plyometrics for increasing sports performance is limited (Carter et al., 2007). Nonetheless, the work by Carter et al., (2007) demonstrated an increase in baseball pitching using adapted ballistic exercises that were movement-specific, which indicates the same principle could be adopted to increase the kinematics of the arm-swing during vertical jumping. Overall, this could potentially lead to an increase in jump height due exclusively to training of the upper-extremities. This requires further exploration.

The key results highlighted within this review show that SSC type movements can be enhanced when utilising a training intervention comprised of plyometric exercises. However, these improvements have only been examined when using lower-extremity plyometric programmes. In contrast, the upper-extremities are repeatedly shown to have a large impact upon jumping ability; however, upper-extremity plyometrics are yet to be explored and examined. This thesis will aim to identify key arm-swing kinematics during vertical jumping and then assess the arm-swing contribution to vertical jump height by comparing CMJ performed with and without arm-swing countermovement. Finally, the main body of this thesis will aim to improve vertical jump ability by training only the upper-extremities using an upper-body plyometric training intervention.

CHAPTER 3

A KINEMATIC ANALYSIS OF THE ARM-SWING COUNTERMOVEMENT DURING VERTICAL JUMPING

3.1 Abstract

The primary aim of this study was to provide a comprehensive examination of the mechanics of the arm-swing during vertical jumping. The lower-extremity mechanics during vertical jumping have been extensively researched indicating mechanisms such as the lower-extremity countermovement as vital for increasing jump height. However, arm-swing contribution to vertical jumping has been reported to increase jump on average by 21.1%, yet despite a larger contributor to jump height than the lower-extremity countermovement, the mechanisms responsible for how the arm-swing yields this increase are not fully understood. Nineteen male club level basketball players (Age: 23.4 ± 3.1 yr; height: 1.84 ± 0.18 m; mass: 82.4 ± 7.5 kg) performed three maximal countermovement jumps using their normal arm-swing technique on a single force platform (1000 Hz). A six segment biomechanical model was created using seven reflective markers placed on anatomical landmarks identified and recorded using a high-speed camera (300 Hz). The data was analysed using seven key arm-swing events representative of the eccentric and concentric phases. Mean peak shoulder ω (748.3 ± 98.8 $\text{deg}\cdot\text{s}^{-1}$) occurred in Phase 2 of the kinematic chain, with the mean peak ω for each distal segment following a pattern of proximal to distal segment rotation (hip→knee→ankle). Mean jump height (44.7 ± 6.5 cm) and mean peak shoulder ω (748.3 ± 98.8 $\text{deg}\cdot\text{s}^{-1}$) were significantly correlated to each other ($r = 0.470$), and a significant contributor to peak arm-swing velocity was the participant's ability to utilise a large amount of their shoulders maximum available shoulder ROM, shown by a positive relationship between the highest jumps performed and utilisation of the highest percentage maximum shoulder ROM. Therefore, the findings from this study demonstrate the arm-swing is a vital mechanism used by athletes to increase jump height, and arm-swing mechanics initiate the vertical jump.

3.2 Introduction

The arm-swing during a vertical countermovement jump (CMJ) is important for increasing ground reaction forces (Feltner et al., 1999; Feltner et al., 2004; Lees et al., 2006), joint torque (Feltner et al., 2004), joint ω (Feltner et al., 1999; Hara et al., 2006), transfer of energy (Lees et al., 2004), and for causing an overall change in segment positioning (Hara et al., 2006). Moreover, when compared to a non-arm swing CMJ, Walsh et al. (2007) observed jump heights that were 23.5% and 25.8% higher with a CMJ with an arm-swing for males and females, respectively. Additionally, in comparison to the contribution from the lower-extremity countermovement (9.2% and 4.7% for males and females, respectively), the arm-swing contribution is more important for increasing jump height. The percentage increase in jump height for CMJA compared to CMJNA as reported by Walsh et al. (2007), is consistent with previous arm-swing contribution studies that demonstrated an average percentage increase of 21.1% (Lees et al., 2004; Lees et al., 2005; Hara et al., 2006; Walsh et al., 2007; Gerodimos et al., 2008; Hara et al., 2008).

Feltner et al. (1999) indicated that the use of an arm-swing during CMJA increased the displacement of the body’s centre of mass (COM) by 14.3 cm when compared to CMJNA. This increase was attributed to two contributing factors: the change in the position of the body’s COM and the increase in vertical ground reaction force (VGRF) (Figure 3.1). The authors highlighted that the initial function of a CMJA was to achieve a maximum vertical displacement of the COM (located within the trunk segment), and noted that raising the arms above the head (mechanism 1; Figure 3.1) contributed 43% towards the increased displacement of the COM at peak flight. Therefore, the largest contributing factor for increasing CMJA peak COM displacement (57%) was created by a different method than raising the COM through the simple upward motion of the arms. Feltner et al. (1999) also suggested that the increase in jump height was also influenced by an increase in VGRF during

CMJA; however, the mechanisms responsible for how the arm-swing yields an increase in VGRF are not fully understood. Comparative studies have demonstrated that an increase in VGRF during CMJA has the potential to increase jump height by up to 12.7% (Feltner et al., 2004; Lees et al., 2004; Walsh et al., 2007; Hara et al., 2008). However, although four mechanisms have been suggested for causing the increased VGRF, consensus amongst researchers has not been reached. These mechanisms are: a decreased hip extensor torque, an increased transfer of energy, an increased lower extremity loading, and a proximal to distal segment loading (Feltner et al. 1999; Feltner et al., 2004; Lees et al., 2004; Moran et al., 2007; Hara et al., 2006). For a detailed description of these, the reader is referred to Chapter 2 of this thesis.

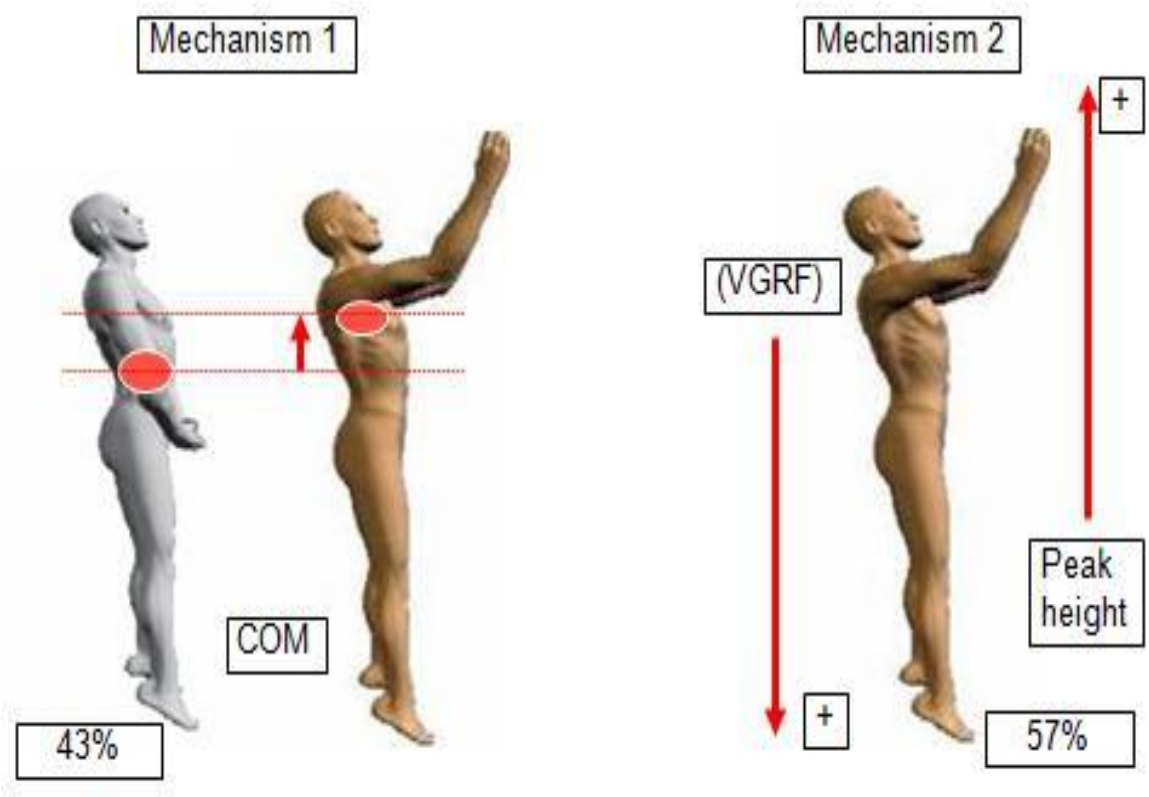


Figure 3.1 Arm-swing contribution during countermovement jumps with an arm-swing (CMJA) to increase the displacement of the body's COM (adapted from Feltner et al., 1999).

In deriving the above explanations, it is noteworthy that previous investigators have analysed the arm-swing during time periods, incorporating key phases that are related to the mechanics of the *lower-body* (Feltner et al., 1999; Lees et al., 2004), and not specific to the mechanics of the upper-body arm-swing. Moreover, previous research has selected the start period for the analyses of the arm-swing contribution to occur mid-way through the arm-swing, at the position immediately prior to the start of the leg extension (Feltner et al., 1999; Lees et al., 2004; Hara et al., 2006; Hara et al., 2008). Whilst Feltner et al. (1999) argued that this was the most appropriate start position, as it referred to the moment of zero vertical velocity (eradicating any contribution from the lower-extremity countermovement), the propulsive phase (extension phase) for the lower body starts late in relation to the whole jump, occurring during the final phase.

Conversely, the arm-swing and trunk movement appear to be highly active prior to this phase (during lower-extremity countermovement) as demonstrated in Figure 3.2, though this has yet to be verified empirically. Interestingly, later work by Feltner et al. (2004) indicated that the arm-swing slows down during the leg propulsion phase, suggesting that its contribution here is sub-maximal, suggesting that acceleration and peak angular velocity of the arm-swing occurs prior to the point of zero vertical velocity (arm propulsion phase). Therefore, it is clear that key arm-swing variables have not been scrutinised adequately with respect to the increase in VGRF and warrant further investigation.

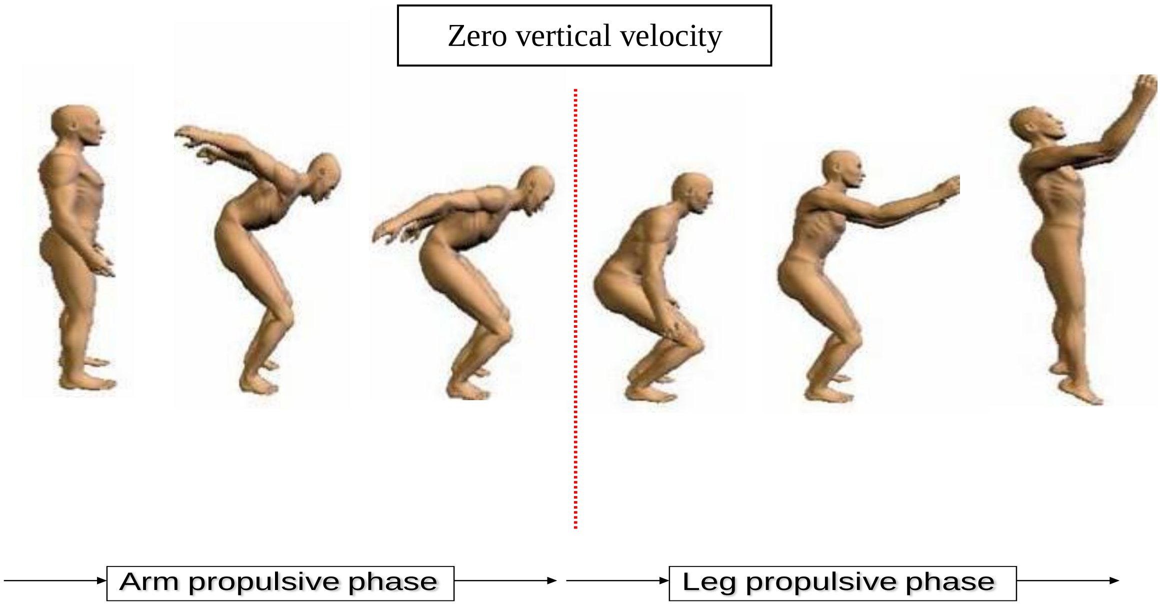


Figure 3.2 Propulsive phases for countermovement jump (CMJ) (adapted from Feltner et al., 1999; Lees et al., 2004).

The aim of this study was to provide a comprehensive examination of the mechanics of the arm-swing during the countermovement (back-swing phase), arm propulsion (down-swing and upswing) and leg propulsion phases of the CMJ. In addition, the study set out to investigate the specific contribution made by the actions of the arm-swing and its effect on the lower-extremities. It was hypothesised that:

1. Upper-extremity peak ω will occur during the down-swing phase of vertical jump performance.
2. Jump height will increase following a peak shoulder ω increase.
3. An increase in the utilisation of the shoulders active range of motion during CMJA will result in an increase in peak shoulder ω.

3.3 Methods

Participants

Nineteen male participants (age 23.4 ± 3.1 yr; stature 1.84 ± 0.18 m; body mass 82.4 ± 7.5 kg) who were active National League basketball players and free of injury, volunteered to participate in the study. Each participant provided written informed consent (Appendix 3.31) to participate and completed a pre-test health questionnaire prior to testing (Appendix 3.32). The study was approved by the University of Chester's Faculty of Applied Sciences Research Ethics Committee (Appendix 3.33).

Study design

The study utilised descriptive design (correlational). Nineteen male participants derived from an *a priori* sample size calculation via the G*Power 3 calculator (Faul, Erdfelder, Lang & Buchner, 2007) completed three countermovement jumps with a normal arm-swing (CMJA) in the same session using their regular technique, 72 hours after a habituation trial. The participants were instructed to jump as high as possible and were not given any performance-related feedback. Their jump height was subsequently used for data analysis. The key dependent variables obtained from kinematic analysis included ω, active range of motion, jump height and jump time.

Procedures

Warm- up protocol

Five minutes before the CMJA assessment each participant performed a standardised warm-up protocol comprising shuttle runs, dynamic and ballistic stretching, and sub-maximal plyometric jumps. The *active* section was performed in a marked area 20 m long by 10 m wide and included four shuttle runs, two high knee runs and two heel-kick runs (De Villarreal, González-Badillo & Izquierdo, 2007; Vetter, 2007). The *dynamic* section was performed in the same area with ballistic stretches at the mid-point (10 m) of each run. Participants performed a single 10 m run for each active stretch with hurdle step-overs, ballistic lunges, and single high leg raises. The sub-maximal plyometric jumps were performed for 20 m, with double squat jumps, single leg hops and calf burnouts (jumping calf raises).

Vertical jumps

Reflective spherical markers (15 mm; Qualysis, Sweden) were placed on seven anatomical landmarks, on the right side of the body to define a six segment biomechanical model (adapted from Lees et al., 2004). Each participant was asked to step into the performance area (1 m x 1 m) with their arms at their sides and pause for two seconds. Each of the three CMJAs was performed with their own technique and each participant jump as high as possible, with 60 s rest between individual jumps. Each jump had to be completed in the performance area to minimise any horizontal displacement, with any jump landing outside the performance area disregarded from the analyses and an extra jump performed.

Two dimensional high-speed kinematic analyses

A fixed single, tripod-mounted, high speed camera (300 Hz, Casio, EX-F1, Japan) was positioned in the frontal plane perpendicular to the performer’s sagittal plane. The recording volume was calibrated using a 1 m x 1 m L-shaped frame (Appendix 3.34). The camera set-up enabled visibility of the wrist, whilst the arms were at full shoulder flexion at the peak height of the VJ. The shutter speed was set at 1/250 s (Payton & Bartlett, 2008) with the auto focus and digital zoom turned off. The exact camera position was identified using the 3, 4, 5 triangle method (Appendix 3.35; Bartlett, 2007). The optical axis of the camera was located by zooming in on a reference marker placed at the same height as the camera at the performance centre point. Two halogen lights (800 W) were placed either side of the camera to enhance image clarity (Bartlett, 2007).

Biomechanical model

A single planar 2D biomechanical model was used for each participant (Figure 3.3). The model was built inferior to superior allowing measurement of ω at the ankle, knee, hip, shoulder, and elbow joints, as well as tracking of the maximum AROM achieved by the shoulder.

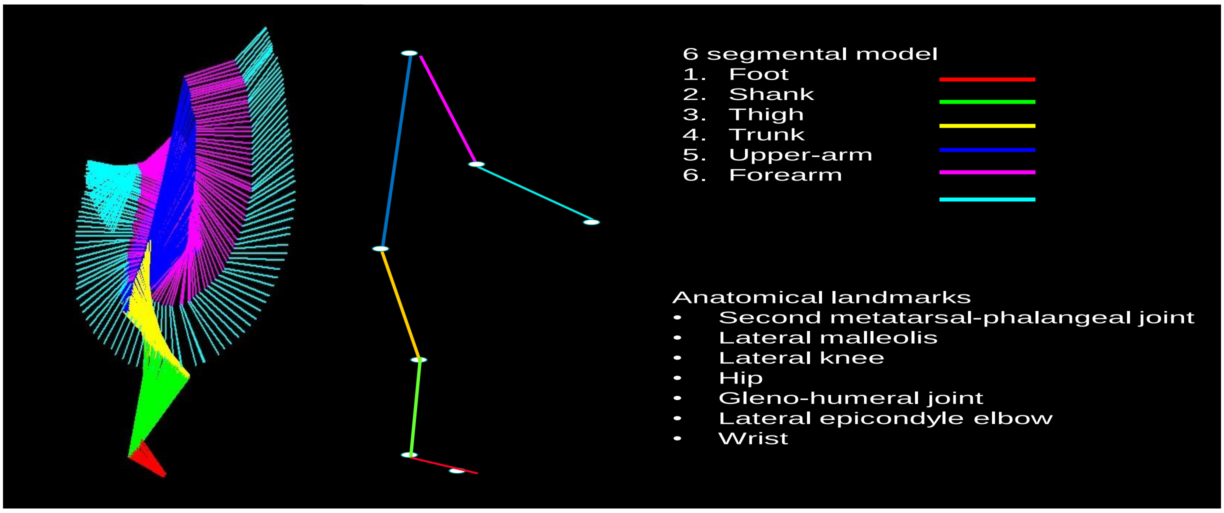


Figure 3.3 Six segmental biomechanical model defined by seven anatomical landmarks (adapted from Lees et al., 2004)

During pilot testing, tracking of the hip marker was lost during the arm down-swing phase, at the point the arms passed over the hip marker. Therefore, additional markers (custom built tracking markers) were added to the transverse plane (anterior and posterior from the mid-point of the hip marker) either side of the original hip marker. These spanned 50 mm from the centre point of the marker, effectively increasing the tracking potential for the centre point of the original hip marker (Figure 3.4). The centre point was calculated as the mid-point between the two distal end locations for each frame of recording and substituted as the hip joint centre.

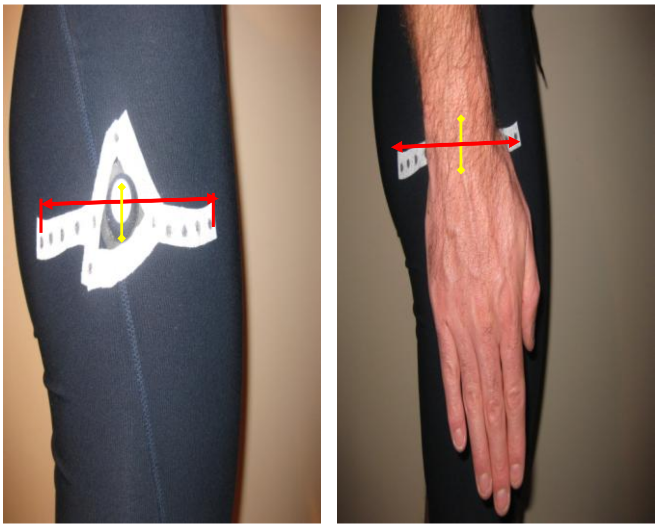


Figure 3.4 Reflective marker tracking trough the transverse plane

Active range of motion (AROM)

The range of motion was measured during an active movement of shoulder hyper-extension, with the participant standing in the anatomical position. A universal goniometer (Baseline, USA) was used to assess the uni-axial rotation of the gleno-humeral joint in the sagittal plane. The angle was measured for the upper-arm segment in reference to rotation around the trunk segment, with the rest of the shoulder stabilised. The start position was at 90 degrees perpendicular to the horizontal (floor) line with the forearms positioned in a neutral position (thumbs in anterior aspect). Active range of motion (AROM) during the CMJA trials was measured using the angular data for the shoulder joint, defined by the proximal (Elbow) and distal joint (Hip) markers, and analysed in Quintic software (Quintic v17, Sweden).

Data processing

Angular kinematics were calculated by the orientation for each joint centre and defined by the proximal segment with distal segment rotation. These were performed following the sequence of the biomechanical model from inferior to superior. The kinematic data were manually digitised using Quintic software (Quintic v17, Sweden) and processed using the biomechanics toolbar (C-Motion v1.02; Vanrenterghem, 2010). The digitised points were smoothed using a Butterworth 4th order zero lag filter at 10 Hz (Lees et al., 2004). Vertical jump height was measured by recording the vertical displacement of the hip joint marker, as representative of the body's COM, and was tracked from take-off to the apex of the jump. Jump height was then measured using Quintic software. The kinematic data were analysed using key movement events throughout the trials and collated at the starting position for each phase (Figure 3.5).

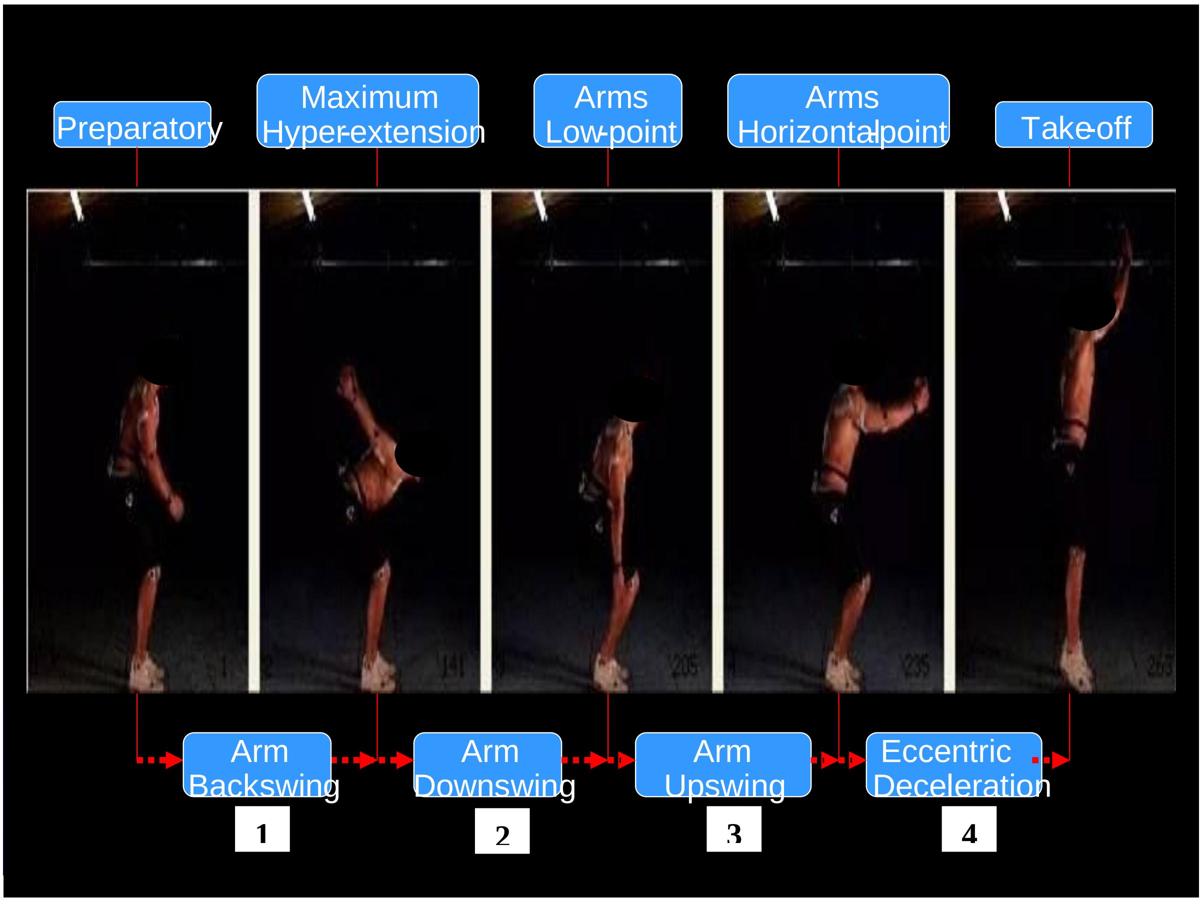


Figure 3.5 Four phases determining the key arm-swing events during CMJA

The events were listed as preparatory, maximum hyper-extension (shoulder), low-point (arms), horizontal point (arms) and take-off, which then determined the arm-swing phases, listed as 1, arm back-swing, 2, arm down-swing, 3, arm up-swing and 4, eccentric deceleration. For ease of interpretation of the results, the key phases were defined by the start and finish points (events), and the peak ω for each joint was reported during the jump (dotted lines; Figure 3.6).

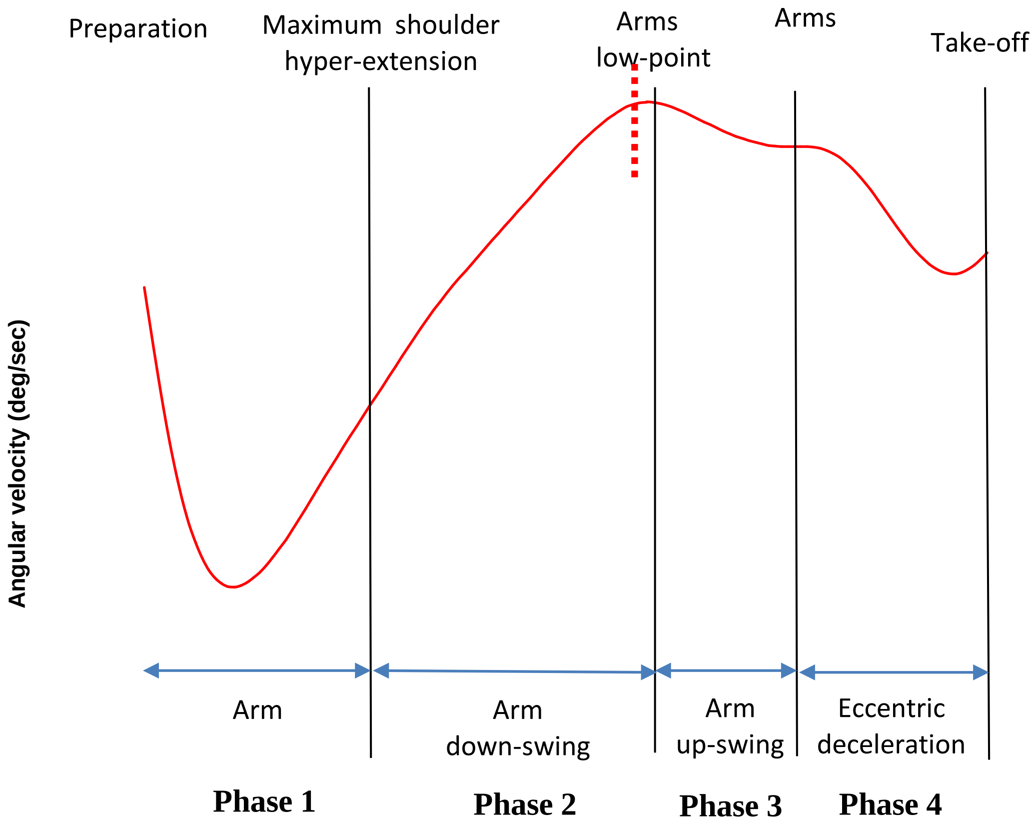


Figure 3.6 Four key phases and five events for the arm-swing during CMJA. (Dotted line = peak ω)

Statistical analyses

Kinematic data were transferred into Microsoft Excel, and descriptive statistics (mean ± SD) were calculated for joint ω, AROM and jump height. Peak joint angular velocities were reported in relation to their sequence (proximal to distal) and phase location. The overall occurrence of each joint peak ω within each phase for all participants was expressed as a percentage relative to time. Additionally, peak angular velocities in relation to key phases and events, and peak shoulder ω, were described for a representative (median) participant. Pearson product-moment correlations were calculated between all dependent variables, with the alpha level set at $P \leq 0.05$. Statistical analysis was carried out using SPSS v. 18.0.

3.4 Results

The descriptive statistics for the key kinematic variables are reported in Table 3.1. Notably, peak ω at the shoulder (748.3 ± 98.8 deg·s^{-1}) occurred first during Phase 2, indicating the shoulder as the proximal rotating upper-body segment in the kinematic chain. This was also apparent for the highest and lowest peak shoulder values (945.3 and 539 deg·s^{-1}, respectively), both occurring during Phase 2. The peak ω for each distal segment to the shoulder occurred during Phase 4, with peak hip, knee and ankle ω following a pattern of lower body triple extension (hip→knee→ankle).

Table 3.1 Mean values (±SD) for individual peak joint angular velocities and the location of each peak joint velocity in respect to the four arm-swing phases.

Joint	**Kinematic variable**	
	Peak ω (deg·s^{-1})	Peak ω phase
Ankle	986.7 ± 573.1	4
Knee	-956.9 ± 278.3	4
Hip	620.8 ± 247.0	4
Shoulder	748.3 ± 98.8	2
Elbow	492 ± 354.6	3

Peak ω phase: location of the peak ω within arm-swing Phases 1-4.

Table 3.2 shows the mean AROM decreased, on average, by 11.3° from pre-test, meaning that they utilised 82.8 ± 10.5% of their available maximum AROM during the CMJA. This resulted in a mean peak displacement of the hip marker of 44.7 ± 6.5 cm.

Table 3.2 Mean values (±SD) for kinematic variables during a CMJA.

Kinematic variable	**Mean value (±SD)**
Hip MK max (cm)	44.7 ± 6.5
Pre-test shoulder AROM (°)	67.6 ± 10.9
CMJA utilised Shoulder AROM (°)	56.3 ± 12.8
% Diff shoulder AROM	82.8 ± 10.5
Total jump time (s)	0.56 ± 0.12

Hip MK max: maximum vertical displacement of hip marker (± SD).

Pre-test AROM: maximum pre-test AROM at the shoulder (hyper-extension).

CMJA AROM: maximum utilised AROM at the shoulder (hyper-extension).

% Diff AROM: percentage difference between shoulder pre-test AROM and AROM utilised.

Total time: total time for each jump.

Of the total mean CMJA time (preparation to take-off), the greatest percentage of time was spent in the arm down-swing phase (34.7 ± 6.9%), decreasing by 50% for time spent during the up-swing, before increasing as the arm-swing decelerated (Table 3.3).

Table 3.3 Mean values (±SD) for jump time and jump phase time percentages.

Arm-swing time variable	**Jump Phase (1-4)**			
	Phase 1 Arm back-swing	**Phase 2** Arm down-swing	**Phase 3** Arm up-swing	**Phase 4** Arm concentric deceleration
Phase time (s)	0.18 ± 0.09	0.2 ± 0.06	0.09 ± 0.01	0.1 ± 0.01
% phase time	30.1 ± 9.5	34.7 ± 6.9	17 ± 3.6	18.1 ± 4.5

Phase time: time spent in each phase.

% Phase time: expressed relative to the total CMJA time.

Table 3.4 highlights that peak knee ω was significantly associated with peak hip and peak elbow, and importantly from an upper-body perspective, that peak shoulder ω was related to both jump height and the active range of movement of the shoulder.

Table 3.4 Pearson correlation coefficients (*r*) between key kinematic and kinetic variables.

	Ankle	Knee	Hip	Shoulder	Elbow	Jump height
Knee	-0.351	-				
Hip	0.219	**-0.784****	-			
Shoulder	-0.047	0.147	-0.202	-		
Elbow	-0.095	**-0.491***	0.358	0.03	-	
Jump height	0.019	-0.021	0.127	**0.470***	0.178	-
% Diff AROM	-0.106	0.049	-0.134	**0.621****	-0.188	0.024

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

The ‘typical’ CMJA profile depicted in Figure 3.7 is characterised by the shoulder (740.2 deg·s^{-1}) and elbow (346 deg·s^{-1}) peak ω occurring during Phase 2 and 3, respectively, prior to an increase in ω of the lower-extremities, where a triple extension movement can be observed during Phase 4, starting proximally at the hip (490.6 deg·s^{-1}) and progressing distally through the knee (-789.3 deg·s^{-1}) and finally the ankle (662.2 deg·s^{-1}).

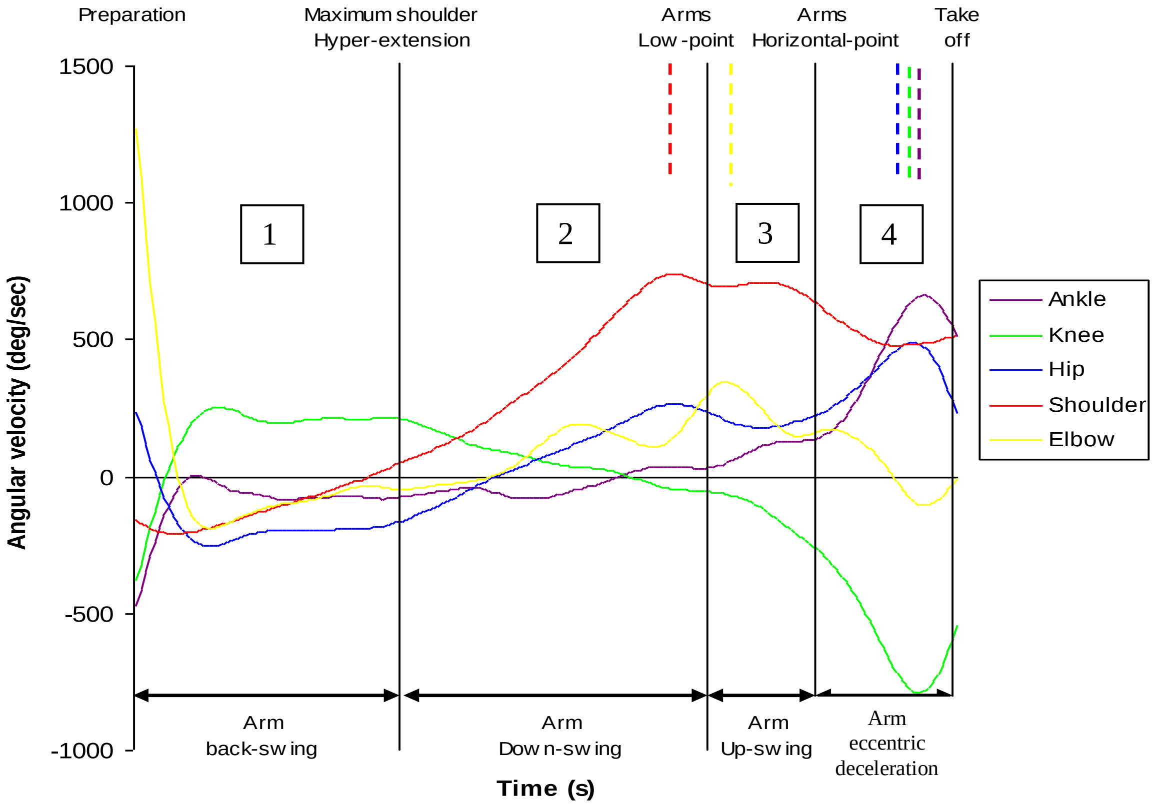


Figure 3.7 Typical (median) peak ω for the ankle, knee, hip, shoulder and elbow. The five dotted lines indicate the position (phase 1-4) and sequence for peak ω for all joints.

The proximal to distal sequence for peak ω is demonstrated by the five coloured dotted lines, representative of the five joints. Collectively (Appendix 3.41), the peak ω at the shoulder joint and elbow occurred during Phase 2 (arm down-swing) and Phase 3 (arm-up-swing), respectively. The peak ω within all three lower-extremity joints occurred during Phase 4 (arm eccentric deceleration), at least one phase after the shoulder ω peak. Key events (black lines 1-5) in Figure 3.7, and are shown in both digital and pictorial views in Figure 3.8.

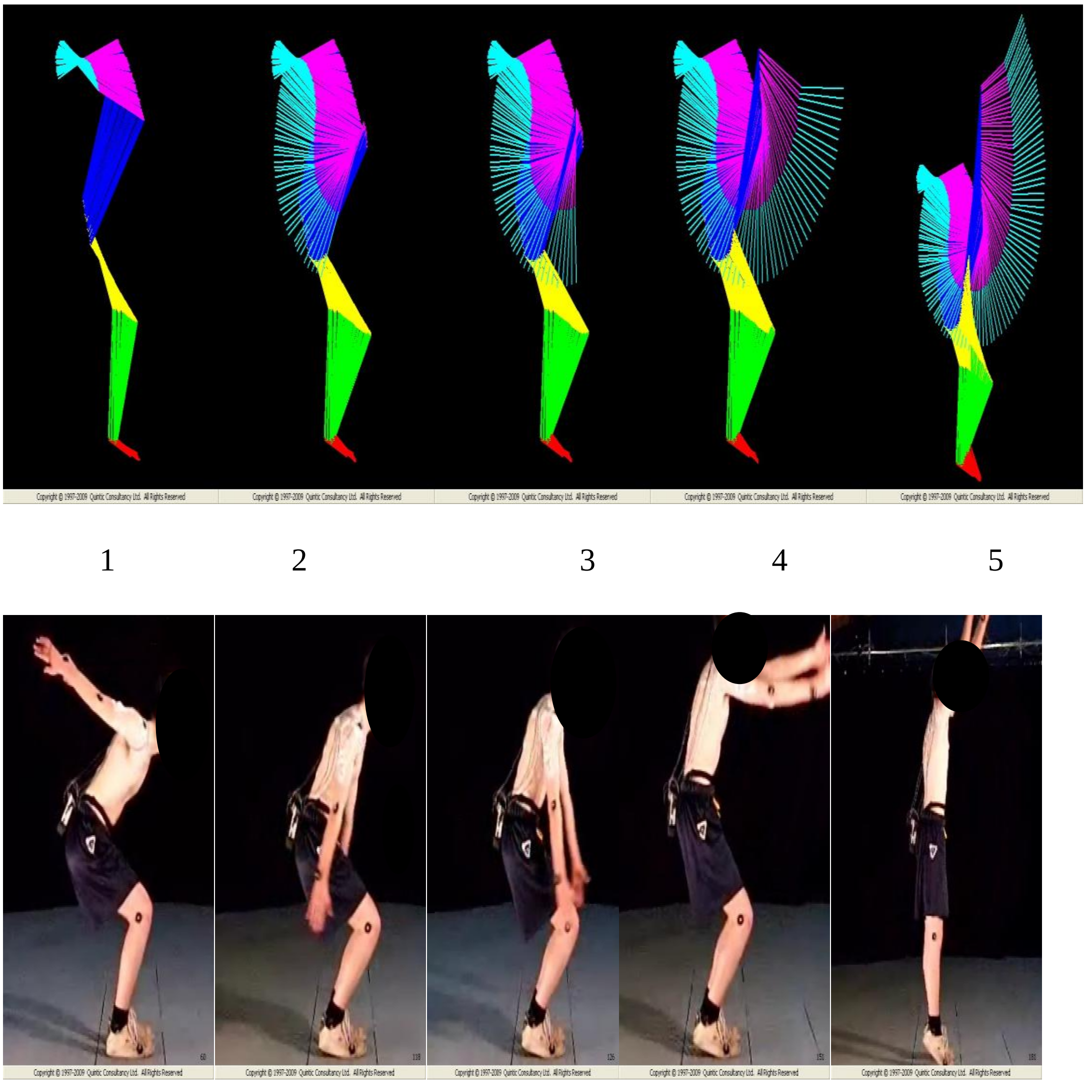


Figure 3.8 Digital and pictorial representation for the key events during the CMJA, shown from left (picture one) to right (picture five); 1, maximum shoulder hyper-extension, 2, Peak shoulder velocity, 3, arms low-point, 4, arms horizontal-point, and 5, take-off.

To examine the mean arm-swing location of the peak ω for the shoulder, its location was plotted in relation to Phase 2 (arm down-swing). This is shown as a single digital trace for the location of the mean peak shoulder ω (-0.008 s) in Figure 3.9. The purple (upper-arm) and light blue (forearm) segments are plotted relative to their rotation around the dark blue (trunk) segment. The mean peak shoulder ω position is shown to occur prior to the low-point of the arms, during the arm-downswing phase. The distribution of peak shoulder ω position values for all participants is plotted in a Figure 3.10.

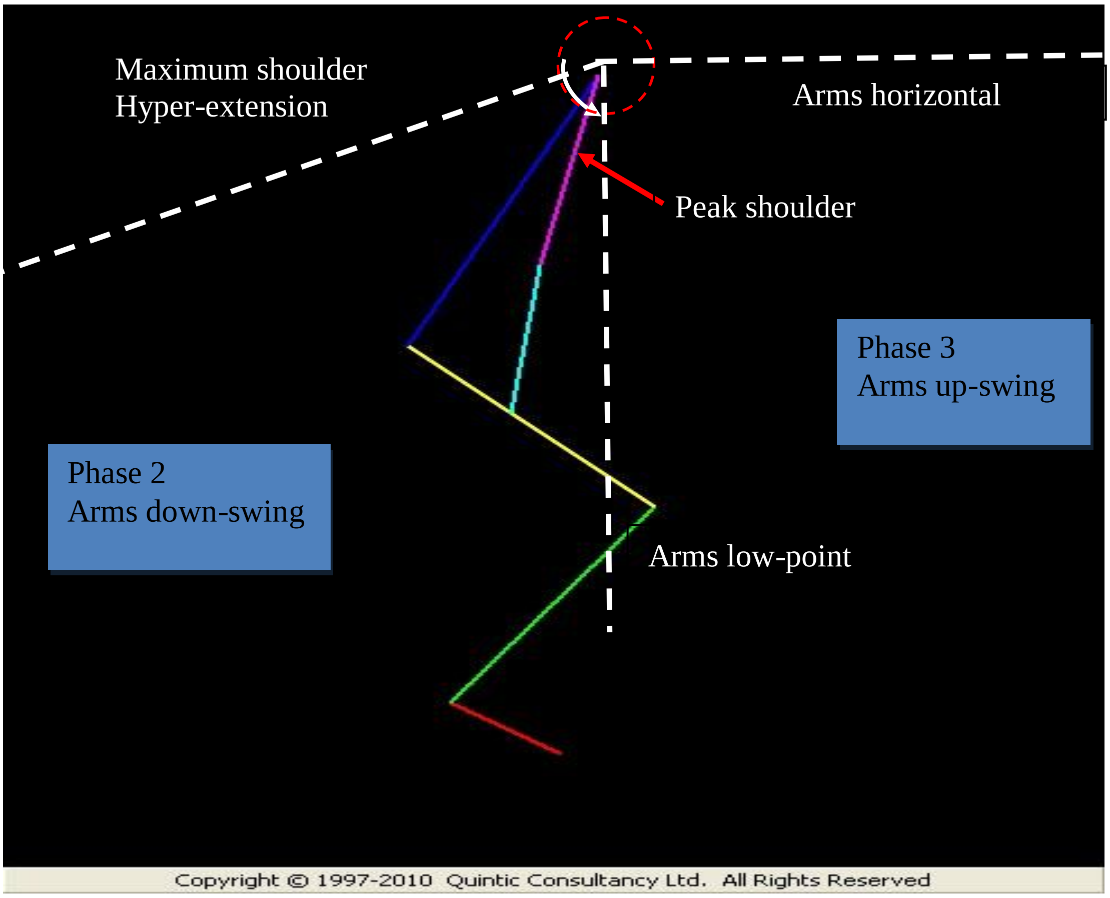


Figure 3.9 Location for the mean peak ω at the shoulder joint (-0.008 s during the arm down-swing).

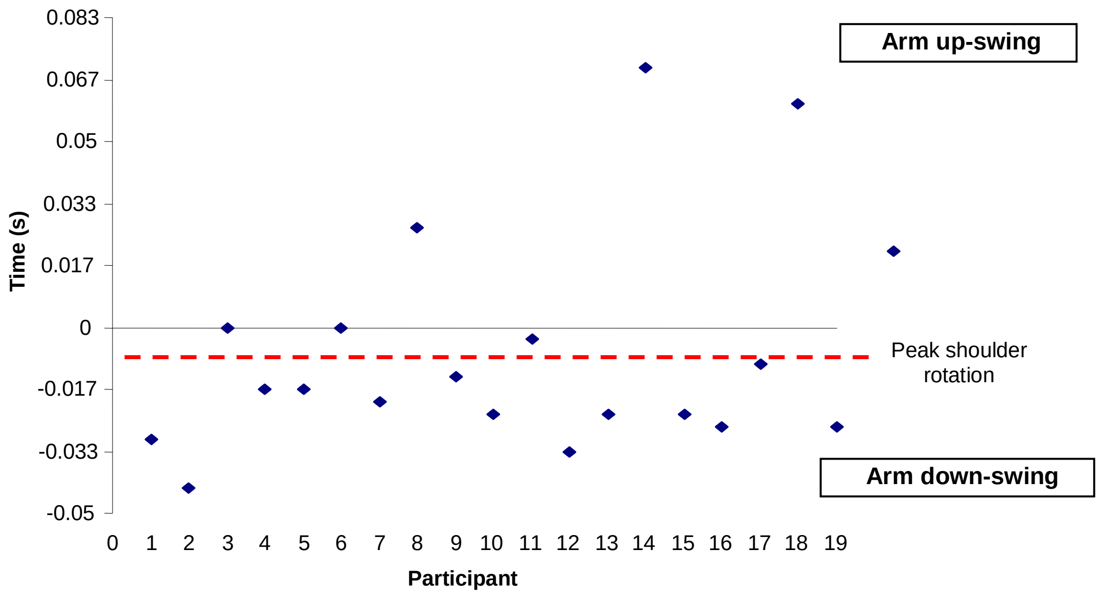


Figure 3.10 Location of individual peak shoulder ω values during CMJA. The red dotted line indicates the mean peak shoulder ω position (-0.008 s).

The horizontal zero line represents the end of the arm down-swing phase (low-point of arms), and the blue data set demonstrate the peak shoulder ω values of each participant relative to the low-point of the arms, occurring 84.2 % prior to the end of Phase 2, and 15.8 % into the arm up-swing phase (Phase 3). The location for mean peak shoulder ω position is indicated by the dotted red line (-0.008 s).

3.5 Discussion

In one of the most detailed examinations of the arm-swing countermovement during CMJ, the current data have confirmed the *a priori* hypotheses with respect to the relationships between the kinematic actions of the arm-swing and vertical jump performance. That is, the arm-swing during a CMJ is highly active prior to the propulsion of the legs, with peak ω at the shoulder (748.3 ± 98.8 deg·s^{-1}) occurring during phase 2 (arm down-swing), and prior to the start of the leg propulsive phase 100% of the time. Arguably, this demonstrates how the arm-swing movement during a CMJ occurs both independently and prior to the leg propulsive phase, initiating the start of the CMJ movement and justifying why arm-swing mechanics requires further exploration.

This study examined the effect of arm-swing velocity on jump height, demonstrating a positive linear relationship for the increase in both shoulder ω and the subsequent increase in jump height ($r = 0.470$). Notably, a significant contributor to peak arm-swing velocity was the participant's ability to utilise a large amount of their shoulders maximum available shoulder ROM, shown by a positive correlation between the highest jumps performed and utilisation of the highest percentage maximum shoulder ROM. This indicates peak shoulder ω and peak utilisation of shoulder ROM as moderate predictors of jump height.

To achieve maximal vertical displacement of the body's COM, joint rotation needs to be sequenced in a proximal to distal pattern (Feltner et al., 2004; Lees et al., 2004). Given the pattern observed by the current sample (shoulder (2.1) → elbow (3.2) → hip (4) → knee (4) → ankle (4)), it can be asserted that an appropriate (effective) CMJA technique was utilised. This is reflected by the mean jump height (44.7 ± 6.5 cm) being comparable to those of competitive volleyball players (48.1 ± 3.6 cm, Bobbert et al., 1996) and National League volleyball players (40.9 ± 3.3 cm, Feltner et al., 1999). Although, in fairness to Feltner et al. (1999), their lower mean jump height (by 7.2 cm) might be explained by the sample being mixed (male and female), and that females have been reported to jump, on average, 14 cm less than males (Walsh et al., 2007).

Jump height during CMJA has previously been shown to increase when utilising a faster arm-swing (Lees et al., 2006), which may be influenced by the amount of AROM utilised (shoulder) during the arm back-swing phase. The AROM of the shoulder was measured both prior to (67.6 ± 10.9°) and during the CMJA trials (56.3 ± 12.8 °), demonstrating percentage difference between AROM available and AROM utilised of 82.8 ± 10.5%. As shoulder AROM is directly related to Phase 1 (arm back-swing) and shoulder rotation is linked to the subsequent Phase 2 (arm down-swing), the significant correlation observed between percentage of AROM used and peak shoulder rotation was not surprising, and may be attributed to an increase in eccentric loading (shoulder flexor muscles) and its subsequent increase in muscle pre-stretch. This suggestion is endorsed by the findings of Moran et al. (2007) who noted that an increase in *lower-extremity* eccentric loading resulted in an increase in vertical jump height, and that the magnitude of eccentric loading was proportional to the amount of AROM utilised. Therefore, the mechanics of the arm down-swing phase, coupled with an increase in eccentric loading (percentage utilised AROM) would lead to an increase in arm-swing velocity, and consequently, an increase in jump height. However, the lack of a direct relationship between percentage utilised AROM (shoulder) and jump height (r = 0.024) was unexpected, and actually infers that the AROM utilised by the upper-extremities is less vital for jump height than that of the lower-extremities. Interestingly, the only variable significantly correlated with jump height was peak shoulder ω (r = 0.470), which might reflect how during Phase 2, the percentage of utilised AROM (shoulder eccentric loading), which is positively correlated with the subsequent peak shoulder ω, can indirectly lead to an increase in jump height.

Moran et al. (2007) proposed that eccentric loading in the lower-extremities during the CMJA is vital for achieving maximum jump height, Moreover, it seems that the same principle applies for the upper-extremities, as the current data reflect a trend in which eccentric loading in the shoulder (created during the arm back-swing phase) leads to an increase in peak shoulder ω and the subsequent increase in jump height. Interestingly, the angular velocities of the lower-extremities (ankle, knee and hip) were unrelated to jump height, emphasising the considerable contribution of the arm swing to jumping performance. More specifically, the timing of the events leading up to the occurrence of peak shoulder ω will directly influence the resultant performance. That is, the peak shoulder ω should occur during the arm down-swing phase (Lees et al., 2004), which is principally governed by the arm back-swing phase (upper-extremity countermovement), and the time spent during each Phase.

In respect to the mean time spent in each jump phase, the greatest percentage of time spent was during the arm down-swing phase, followed by a marked decrease during the up-swing phase. Indeed, the rapid decrease in time spent during the arm up-swing phase links directly to the occurrence of peak shoulder ω at the end of the arm down-swing phase, meaning the arms were travelling faster during the up-swing. However, the fact that peak shoulder ω occurred during the longest phase percentage time-wise (arm down-swing) and not during the subsequent faster and shorter percentage time phase (arm up-swing), indicates the importance of the arm down-swing phase in relation to overall CMJA performance. Interestingly, during Phase 4 (arms eccentric deceleration), which occurs simultaneously to lower-extremity propulsion during CMJA (Bobbert et al., 1999; Feltner et al. 1999; Feltner et al., 2004; Moran et al., 2007), the mean arm-swing velocity decreased slightly, as demonstrated by the higher percentage time compared to Phase 3 (arm up-swing).

Phases 3 and 4 were defined by previous investigators to examine the arm-swing mechanics during CMJA (Feltner et al., 1999; Feltner et al., 2004; Lees et al., 2004) relative to the lower-extremity propulsion phase. However, in respect of the arm-swing mechanics during a full CMJA, the findings of Phases 1 and 2 in this study present a strong argument for why arm-swing mechanics need be examined earlier than Phase 3, that is, the point in which elite basketball players achieve their maximum arm-swing propulsion (Phase 2). This is vital for understanding the full role of the arm-swing during CMJA, and not just how the arm-swing occurs in reference to the leg propulsion phase (Phase 3). Furthermore, in respect to the occurrence of peak shoulder ω in Phase 2, and the relative longer time spent in that phase, the overall CMJA technique observed in this study demonstrated elite basketball players performing CMJA as a homogeneous group, so therefore, similar trends can be observed in each participant.

The characteristic CMJA peak angular velocities for the current sample (represented by the median participant, Figure 3.7) highlight that the peak shoulder ω (720.2 $\text{deg}\cdot\text{s}^{-1}$), acting as the proximal rotating segment, occurred during the arm down-swing phase, but after Phase 1 and the early stages of Phase 2, shoulder ω begins to decrease. Knowledge of such antecedents of peak shoulder ω is therefore vital for explaining how the arm-swing reaches this peak (arm-back swing and early down-swing).

Figure 3.7 shows that prior to maximum shoulder hyper-extension, the upper-extremities rotate proportionally as the arm segments act as a counterbalance to the active positioning of the trunk (upper-body countermovement). The upper-body countermovement (arm back-swing) has the effect of creating an opposing rapid trunk flexion, which according to Vanrenterghem et al. (2008), would alter the position of the body’s COM. It appears that jumps performed with an arm-swing (compared to those that are not) create an increase in peak trunk flexion (+5°) and the rate at which peak trunk flexion is achieved (+4%). This has the effect of increasing the amount of available hip flexion during the lower body countermovement, which according to Moran et al. (2007) can increase eccentric loading of the lower body musculature. In addition, the increase in trunk flexion will follow a pattern of proximal to distal loading, developing an increase in flexion at the hip, knee and ankle. Therefore, during the subsequent trunk extension, the trunk will have further to rotate, increasing the time available to produce force. As much of the body mass is located within the trunk segment (Hara et al., 2008), increasing the rate and magnitude of its rotation during trunk extension may help increase jump height, and by doing so reinforces the role of the upper-body countermovement in the execution of a CMJA.

During Phase 2 (Figure 3.7), the arms start the down-swing phase towards their low-point; whilst knee and ankle rotation continue to actively flex the lower-extremities (lower-body countermovement). The arm-swing rapidly increases towards its peak value (740.2 $\text{deg}\cdot\text{s}^{-1}$), acting as the initiator in a proximal to distal sequence of joint extension, and the rapid arm-flexion creates a rotational force at the hip causing an opposing hip extension (Feltner et al., 2004). The observed increase in hip rotation is primarily due to active trunk positioning (trunk extension) and not hip extension (thigh extension). The trunk is initially extended during the lower-extremity countermovement, changing the location of the COM, and priming the lower-extremities for joint extension. This is highlighted by the first small peak in the hip velocity trace (266.2 $\text{deg}\cdot\text{s}^{-1}$) during the same frame (118) as the peak shoulder ω (740.2 $\text{deg}\cdot\text{s}^{-1}$), and is an example of how the arm down-swing directly influences the lower-extremities propulsion (proximal to distal). The method of using the arm-swing to actively position the trunk has been considered by previous research (Feltner et al., 2004; Hara et al., 2008; Vanrenterghem et al., 2008), however, actively increasing the rate of trunk rotation via arm-swing propulsion has not been fully explored. An increase in trunk flexion during the lower body countermovement and trunk extension during the arm down-swing phase can only be achieved if peak shoulder ω occurs prior to the start of the leg propulsive phase (Phase 3).

Arguably, and in accordance with Lees et al. (2004), the peak shoulder ω occurring prior to the lower-extremity propulsive phase would facilitate optimal conditions for the transfer of KE from the upper to lower-extremities, indicating energy built up by arm segment rotation would be transferred from the shoulder to the hip. This creates an energy transfer process from the upper to lower-extremities, linked to lower body muscular contraction. As the hip extensor muscles contract eccentrically during the countermovement (arm down-swing phase), KE production is increased by upper segmental rotation. As the hip extensor muscles reach maximum flexion, they contract isometrically and KE is transferred from the shoulder to the hip as PE, and stored awaiting reutilisation. Finally, the hip extensor muscles contract concentrically during the leg propulsive phase; and the PE is reutilised as KE by the upper extremities. Later work by Lees et al. (2006) suggested increasing KE production by utilising a more vigorous arm-swing could further enhance the transfer of energy. The aforementioned evidence suggests that the transfer of KE is reliant on the speed of the arm-swing, which is dependent on both the rate and magnitude of arm-swing velocity, and therefore the kinematics (arm-swing ω and AROM) of the arm down-swing phase, and the previous arm-swing countermovement (back-swing phase).

Evidence of increased KE production leading to an increase in vertical jump height (Lees et al., 2004; Lees et al., 2006) indicates that an increase in arm-swing velocity during the down-swing phase should increase the availability of KE to be used as a ‘pull’ mechanism at take-off. The work by Vanrenterghem et al. (2008) also indicated a positive relationship between arm-swing velocity and trunk flexion, implicating the arms as the proximal rotating segment during a CMJA. Hara et al. (2006) noted the arms as the initiator in the proximal to distal kinematic chain of segment rotation during CMJA, suggesting any increase in arm-swing velocity will increase the subsequent rotating joint’s velocity. Moran et al. (2007) argue that this would affect lower-extremity loading, with an increase in arm-swing velocity leading to an increased trunk flexion, and finally an increase in the pre-stretch of the lower-extremity musculature. The increase in eccentric activity would develop advantageous conditions in the subsequent concentric performance, and when related to CMJA, would increase jump height (Bobbert et al., 1996; Moran et al., 2007). In the current study, the increased peak shoulder ω during the down-swing phase, eccentric loading and proximal to distal rotation, has highlighted the importance of the arm-swing mechanics during the upper-extremity countermovement as this is the development phase prior to the occurrence of peak shoulder ω.

Phase 3 represents the initial arm up-swing phase, as the legs make the transition from flexion (loading) to extension (propulsion), and the arms complete the cycle of trunk positioning. Following peak shoulder ω, the arms rotate to reach their low point as they pass the vertical. Arm-swing ω demonstrates a slight decrease (740.2 - 694.2 $\text{deg}\cdot\text{s}^{-1}$) before being maintained throughout the first 75% of the up-swing phase. The initial decrease in shoulder rotation may have been caused by the gravitational pull on the arm segment, occurring immediately as the arms rotate upwards; however, the decrease in hip extension is not created by gravity, but due to a complex series of events as the arms reach their low point. Feltner et al. (1999) describe the arm-swing low point as the moment when rotational force reaches its peak value in the vertical direction, yet minimal in the horizontal direction. This suggests a period when rotational force transfers into VGRF and consequently during the subsequent period, the decrease in arm-swing rotation creates a decrease in trunk rotation, causing the rate of hip extension to decrease.

Work by Feltner et al. (2004) demonstrated that a decrease in extensor torque at the hip delays the muscle recruitment of fast twitch muscle fibres. A CMJ performed with no arm-swing creates less trunk inclination (Vanrenterghem et al., 2008), and therefore initiates early muscle excitation in the leg muscles to act as a counterbalance. In turn, this forces the fast twitch motor units to fatigue too early in the leg propulsive phase. If peak shoulder ω can be achieved during the down-swing phase, the associated decrease in hip extension will cause a delay in this recruitment, acting as an enhancement mechanism to allow a more explosive delayed contraction to be utilised during late leg propulsive phase (Feltner et al., 1999). This would implicate the arm-swing further enhancing the conditions of the lower-extremities;

therefore, it should be argued that the arm-swing phase prior to this moment (down-swing phase) is critical in producing the optimal conditions in the lower-extremities for maximising jump height.

Phase 4 is the start of the arms deceleration and change-over from arm propulsion to leg propulsion. Angular velocity at the shoulder rapidly decreases during this phase (611.4 – 479.8 deg·s^{-1}) whilst the hip, knee and ankle angular velocities rapidly increase to their peak values (hip: 236.9 – 490.5 deg·s^{-1}; knee: -288.3 - -789.2 deg·s^{-1}; and ankle: 150.7 – 662.2 deg·s^{-1}). Peak ω at the hip, knee and ankle occurs in a proximal to distal sequence, creating a rapid triple extension of the lower-body just prior to take-off. This creates a maximal displacement of the body's COM immediately after peak ankle rotation from the plantar flexor muscles. Whilst the arm-swing during this late phase has decreased, they are still active in creating an opposing force on the trunk segment. The digital and pictorial representations of each CMJA phase and the location of the peak shoulder ω shown in Figure 3.9, demonstrate the large difference in the amount of activity between the upper-extremities (highly active) and lower-extremities (minimally active) prior to the arms horizontal-point, and the change-over to leg propulsion immediately prior to take-off. This suggests an arm propulsive phase during early CMJA performance, and a leg propulsive phase during late CMJA performance.

The current evidence has shown the importance for the peak arm-swing rotation to occur during the down-swing phase of CMJA (Feltner et al. 1999., Feltner et al., 2004; Lees et al., 2004; Moran et al., 2007; Hara et al., 2006). This study involving National League basketball players, has demonstrated that peak shoulder ω is utilised during the arm down-swing phase, and offers a new perspective on how important the role of the arm-swing is in vertical jumping. A single biomechanical model trace represents the frame location from the high speed camera data, with the mean peak shoulder ω location occurring 2.42 frames before the arms low-point. This is further demonstrated when examining the absolute values (Figure 3.10) of each participant's peak shoulder ω location, occurring 84.2% in the down-swing phase and 15.8% during up-swing phase. The 84.2% occurrence during the down-swing phase shows that the majority of the examined population demonstrate a similar use of the arm-swing during CMJA. This was not unexpected given the standard at which the participants perform their sport and the importance of jumping as a performance indicator (Bishop & Wright, 2006).

The use of an upper-extremity countermovement prior to the subsequent arm-swing propulsion phases has been shown to be an important consideration during CMJA; however, this study is limited empirically in understanding how the upper-extremity countermovement contribution affects CMJA performance. That is, how the effect of performing an arm-swing with and without an arm-swing countermovement will act upon the overall CMJA performance. Research examining the contribution of the lower-extremity countermovement section to CMJA performance, has shown an increase in performance when comparing jumps with and without a countermovement (Bobbert et al., 1996; Gerodimos et al., 2008), and a similar investigation for the upper-extremity countermovement is required. Furthermore, even though the contributing factors for improving arm-swing velocity are often termed 'single-planar movements' (Lees et al., 2004), that is, coupled flexion and extension movements in the sagittal plane, the use of three dimensional analyses may offer a new and even more comprehensive analysis of the CMJA. The relationship between the optimal required AROM during CMJA and peak shoulder ω was not fully explored in this study, and warrants further investigation.

3.6 Conclusion

In respect to both total jump time and percentage time within each jump phase, the current elite basketball players performed CMJA as a homogeneous group, demonstrating very similar jump characteristics, and similar to those examined in elite level volleyball. Examination of the arm-swing mechanics during CMJA highlighted the arm-swing acting as the initiator in the proximal to distal sequence of joint rotation. The primary focus for the arm-swing during vertical jump performance is two-fold, increasing the time available for lower-extremity force production (creating advantageous conditions in the lower-extremities), as well as creating a rapid upward movement of the body's COM following an active repositioning of the trunk (creating advantageous conditions in the upper-extremities) (Vanrenterghem et al., 2008). Furthermore, the most important factors to impact upon these two associated aspects that are both directly affected by the arm-swing, is the increase in shoulder ω and its location within the arm down-swing phase.

The current study demonstrated that elite basketball players utilise an arm-swing inherent of a peak shoulder ω occurring in the arm-downswing phase. Interestingly, the current study showed that the percentage of utilised AROM (shoulder eccentric loading) demonstrated a strong relationship with peak shoulder ω, which in turn was positively related to jump height. The increase in arm segment rotation should also contribute towards lower-extremity eccentric loading, transfer of KE and distal joint velocity. Increasing the use of the available AROM during CMJA may increase both the rate and magnitude of the arm-swing, and should be considered for improving jump height; however, there is no indication on the optimal level for how much AROM is required.

Similar to lower-extremity research showing an increase in vertical jump height when using a lower-extremity countermovement, the back-swing phase of the arm-swing (upper-extremity countermovement) will influence the proceeding performance of the arm down-swing phase. Therefore, a comparative study of CMJA performed with and without a countermovement arm-swing warrants further investigation. However, this section of the arm-swing during CMJA has not been considered by previous investigators, and is yet to be empirically examined.

CHAPTER 4

THE CONTRIBUTION OF THE ARM-SWING COUNTERMOVEMENT TO VERTICAL JUMP PERFORMANCE

The contents of this chapter were presented at the following conference:

Connell, R., Worsfold, P., Twist, C., & Lamb, K. (2011). An investigation into the arm-swing stretch-shortening cycle during vertical jumping. British Association of Sport and Exercise Sciences, Biomechanics Interest Group (BIG) national conference, University of Chichester, 2011.

4.1 Abstract

The aim of this study was to examine the contribution of the arm-swing countermovement (arm back-swing) to vertical jump performance. The same mechanism in the lower-extremities has been shown to increase jump height by an average of 7.6 % when using a lower-body countermovement. Yet, despite overall arm-swing contribution increasing jump height between 18 to 26%, the countermovement mechanism for the upper-body during the arm-swing has not been examined. Nineteen male club level basketball players (Age: 23.4 ± 3.1 yr; height: 1.84 ± 0.18 m; mass: 82.4 ± 7.5 kg) performed three maximal counter movement jumps using a loaded arm-swing (SSC) and a concentric only arm-swing (No SSC). A six segment biomechanical model was created using seven reflective markers placed on anatomical landmarks and recorded using a high-speed camera (300 Hz).The data was analysed using seven key arm-swing events representative of the eccentric and concentric phases. Mean peak ω ($748.3 \pm 98.8 \geq 680.8 \pm 84.3$ deg·s^{-1}) and peak height ($44.7 \pm 6.5 \geq 38.5 \pm 8.6$ cm) were significantly higher during the SSC condition. Furthermore, utilisation of the SSC by the arm-swing within CMJ decreased the time it took to achieve peak ω of the shoulder, therefore, enabling the peak shoulder velocity to occur during the down swing phase of the arm-swing (100%). In contrast, the peak ω during the no SSC condition occurred during the upswing phase (79%).

4.2 Introduction

A countermovement prior to an opposing sporting movement, such as flexing the legs during vertical jumping, is important for improving sports performance such as increasing jump height (Gerodimos et al., 2008; Gamble, 2010), as it enhances the conditions for a muscle to contract concentrically, yielding more force than without the movement (Bobbert et al., 1996; Bobbert et al., 2005). Whilst the evidence for such an improvement has been observed in many lower body movements, such as human locomotion (Lichtwark, Bougoulias & Wilson, 2007) and vertical jumping (Bobbert et al., 1996; McBride et al., 2008), it also exists for more complex upper-body movements, such as the tennis serve (Elliott, Fleisig, Nicholls & Escamilia, 2003), golf drive (Fletcher & Hartwell, 2004) and the football throw-in (Marques, Marinho & Van Der Tillaar, 2010).

The suggested mechanisms responsible for the benefits provided by countermovement's during a concentric movement are numerous and include the active state development in muscles (Bobbert et al., 1996; Bobbert et al., 2005), potentiation of the contractile components (Binder-McCleod et al., 2002), the stretch reflex system (Komi & Gollhofer, 1997; Gerodimos et al., 2008), the stretch-shortening cycle (SSC) (McBride et al., 2008; Gerodimos et al., 2008) and the effective storage and utilisation of elastic energy (Bobbert et al., 1996; McBride et al., 2008). (For a detailed description of these, the reader is referred to Chapter 2 of this thesis). Whether all these mechanisms are involved, to a lesser or larger extent, has not been established, but a link between them appears to be the role of the SSC coupled with the effective storage and utilisation of elastic energy, as countermovement's utilise the SSC during eccentric loading, leading to an increase in concentric performance, faster transition time (eccentric concentric coupling), and subsequently the development of neuromuscular stiffness (Bobbert et al., 1996; Komi & Gollhofer, 1997; Earp et al., 2010).

Therefore, to achieve maximum concentric performance during sporting actions, the use of a countermovement, and activation of the SSC, is advocated.

Contribution of the lower-body SSC has been studied during vertical jump performance by comparing SJ and CMJ (Gerodimos et al., 2008). Typically, an increase of 3.5 ± 0.82 cm (7.6 ± 1.5 %) is achieved when utilising the SSC in the CMJ condition over the SJ condition (Table 4.1). Moreover, investigators have demonstrated that larger VGRF is generated at a greater rate when the lower-body SSC is used during vertical jump performance (McBride et al., 2008; Gerodimos et al., 2008; Hara et al., 2008). The highest values on average are observed as the jumper reaches their lowest point (during late eccentric performance), leading to faster rate of force development. Further, it is rare that the positive increase in force development occurs during the concentric phase; therefore, the rate of force development (RFD) could also be referred to as the loading rate. Importantly, the loading rate can vary widely between individuals, yet investigators have shown this often occurs prior to the propulsive phase, further reinforcing the importance of using a countermovement prior to vertical jump performance.

Table 4.1 Comparative (lower extremity) studies for vertical jumping with (CMJ) and without a countermovement (SJ)

Study	Increase in VJ height for CMJ versus SJ Jump height	
	cm	%
McBride et al. (2008)	3	8.1
Gerodimos et al. (2008)	3.2	9.1
Hara et al. (2008)	5	8.6
Bobbert et al. (2005)	3.4	7.6
Bobbert et al. (1996)	3.1	6.9
Earp et al. (2010)	2.5	4.6
Walsh et al. (2007)	4	8.2
Mean ± SD	3.5 ± 0.8	7.6 ± 1.5

It is noteworthy, however, that whilst the countermovement's contribution to vertical jumping has been extensively researched in lower-extremities, its role and effectiveness within upper-extremity movements has received little attention. This is surprising given that sporting actions that incorporate vertical jumps (such as basketball and volleyball) also utilise upper body movements (arm-swing) that are preceded by an arm-swing countermovement prior to the desired concentric movement (Figure 4.1) in order to enhance performance (see Chapters 3.5 and 3.6 of this thesis). Furthermore, even though peak arm-swing velocity should occur during the arm down-swing phase (see Chapters 3.4 and 3.5), the contribution from the arm-swing during the preceding phase (arm back-swing, countermovement) has not been empirically examined.

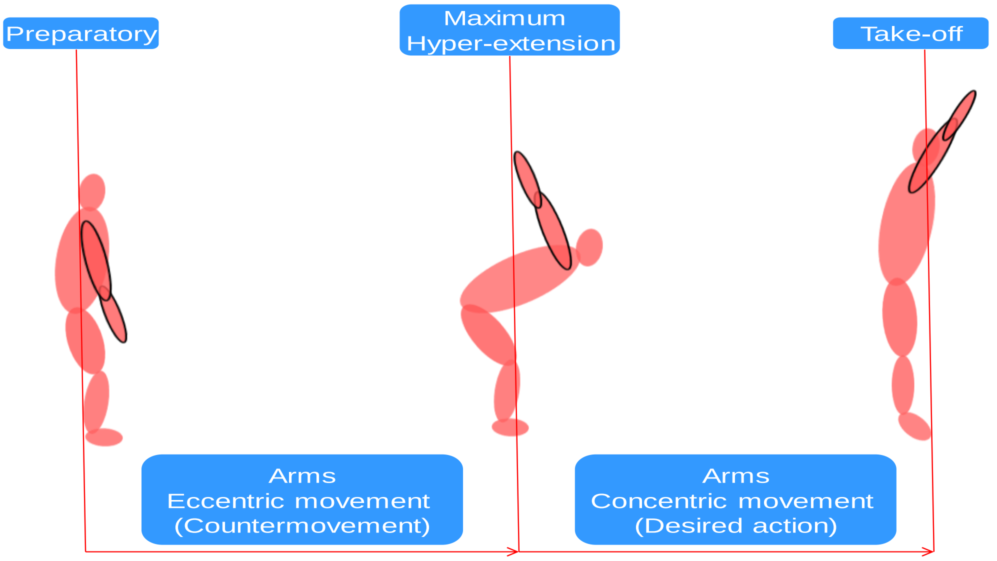


Figure 4.1 Arm countermovement during CMJ (adapted from Feltner et al., 1999; Lees et al., 2004)

Upper-extremity countermovement's have been examined for bench press exercises (Doan et al., 2002), explosive bench throws (Newton et al., 1997), and isolated movements such as elbow flexion (Miyaguchi et al., 2008) and elbow extension (Miyamoto et al., 2010). Typically, the aim was to assess the contribution of the SSC by comparing movement with and without a countermovement, that is, one with a preceding eccentric movement and one with a concentric only movement. The use of a preceding countermovement increased the subsequent concentric performance of the arms, shown by an increase in average concentric velocity, average force and peak force (Newton et al., 1997), Furthermore, there was significantly greater surface muscle activity recorded from the pectoralis major and triceps brachii during the initial 100 ms of the concentric phase when movement was preceded by a countermovement, indicating the utilisation of the SSC through the effective increase in muscle pre-stretch. Moreover, this has been shown to increase the muscle active state (Bobbert et al., 1999), use of the stretch reflex system (Komi & Gollhofer, 1997) and the increased utilisation of elastic energy (Lees et al., 2004).

Interestingly, the increase in these kinematic variables was achieved with a decrease in the concentric time period during SSC condition (-264 $m \cdot s^{-1}$) when compared to the concentric only bench throws (Newton et al., 1997), indicating that the force produced at the start of the concentric phase was higher and led to a faster concentric contraction. Similar responses on concentric performance when utilising a preceding countermovement was observed during isolated elbow flexion (Miyaguchi et al., 2008), demonstrating an increase in initial concentric arm velocity (+0.18 $m \cdot s^{-1}$) and peak arm swing velocity (+0.04 $m \cdot s^{-1}$) when performed with a countermovement. Even though these increases were small in comparison to overall arm-swing velocity, they effectively led to a significantly greater increase in muscle strength (+ 17%), suggesting that even small changes in arm-swing velocity could increase sports performance. Miyamoto et al. (2010) examined the optimal load for elbow extension with loads ranging from 2.5 to 15 kg and movements performed with (SSC) and without a countermovement (concentric only), indicating a load in the middle of a parabolic curve (7.5 kg) as optimal and demonstrating that eccentric loads that were too high or too low negatively impacted upon elbow extension (Miyamoto et al., 2010). This may present further evidence of the balance between the positive increase in reutilisation of elastic energy and the negative increase in GTO activation as shown in previous SSC studies (Lees et al., 2004; Komi et al., 1997) (see Chapters 2.2 and 2.4). However, the findings are only representative of the movements examined and even though these movements were not sport specific, they indicate that utilising a countermovement prior to concentric performance in the upper-extremities will have a positive impact upon sports that use upper-extremity movements that are preceded by a countermovement.

During CMJ, peak arm-swing velocity occurs during the arm-down swing phase (see Chapter 3.5) which is the phase that follows the arm back-swing phase, which acts as the arm-swing countermovement. To fully understand the contribution from the arm countermovement, the arm-swing during CMJ needs to be examined with and without a countermovement, that is, a comparison between a concentric only arm-swing and a countermovement arm-swing. To date this has not been previously examined. Furthermore, During CMJ, peak arm-swing velocity and jump height are effectively increased (directly and indirectly, respectively) when a greater amount of the available shoulder active range of motion is utilised (see Chapters 3.5 and 3.6). The percentage of utilised active range of motion at the shoulder will depend upon the individual's ability to swing their arms back as far as possible (Lees et al., 2004), as well as the coupling between muscle pre-stretch during the arm-swing countermovement (eccentric, arm back-swing phase) and the arm-swing propulsion phase (concentric, arm down-swing). Therefore, the active range of motion utilised during arm-swings performed with and without a countermovement will be assessed in the current study, and its affect upon arm-swing velocity will be a main area of focus. It was hypothesised that:

1. Peak shoulder ω will be higher in the CMJ performed with an arm-swing countermovement.
2. Peak shoulder ω will occur at a faster speed in the CMJ performed with an arm-swing countermovement.
3. Jump height will be greater in the CMJ performed with an arm-swing countermovement.
4. The AROM utilised by the shoulder during the CMJ performed with an arm-swing countermovement will be less than that of the maximum used during the CMJ with no countermovement arm-swing.

4.3 Methods

Participants

This study used the same participants, sampling strategy, informed consent, and pre-test health questionnaire prior to testing as the previous study and the reader is referred to Chapter 3.3 of this thesis. The study was approved by the University of Chester's Faculty of Applied Sciences Research Ethics Committee (see Appendix 4.31).

Study design

The study utilised a repeated measures design in which 19 male participants derived from an *a priori* sample size calculation via the G*Power 3 calculator (Faul, Erdfelder, Lang & Buchner, 2007) completed three countermovement jumps both with and without a countermovement arm-swing, at the University of Chester biomechanics laboratory. In both jump conditions, participants jumped as high as possible, and all jump conditions were randomised. All jumps were performed in the same session using their usual jump technique and with no performance-related feedback, 72 hours after a habituation trial. Their jump height was subsequently used for data analysis. The key independent variable was the arm-swing start position (countermovement or no countermovement (concentric only)). The key dependent variables obtained from kinematic analyses included ω and active range of motion (both pre-test and during) both measured at each joint, jump height and jump phase time. These variables were analysed for both the CMJ with and without a countermovement arm-swing.

Procedures

Vertical jumps

After completion of the same warm-up protocol as used in the previous study (see Chapter 3), each participant was asked to step into the kinematic performance area (1 m x 1 m) with their arms at their sides and pause for two seconds. Thereafter, a total of six jumps were performed, with 60 s rest between individual jumps. The jumps had to be completed in the performance area to minimise any horizontal displacement. Any jump that was completed outside of the performance area was disregarded from the analyses and an extra jump was performed. Figure 4.2 shows the arm-swing start position in both jump conditions, starting at the participant's normal resting position (as close to 0° as possible) in the jumps performed with an arm-swing countermovement (A), and then being drawn back to maximum shoulder hyper-extension during the CMJ performance. The arm-swing during the CMJ condition with no arm-swing countermovement started at the participant's arms at the point of maximum shoulder hyper-extension (B), and did not swing forward until the participant had reached their bottom position. This allowed full use of the legs' countermovement in both jumps and ensured a concentric only movement was utilised when the no arm-swing countermovement CMJ were performed (Hara et al., 2006). The participant's forearm was held in their natural position within the transverse plane throughout each jump in both jump conditions.

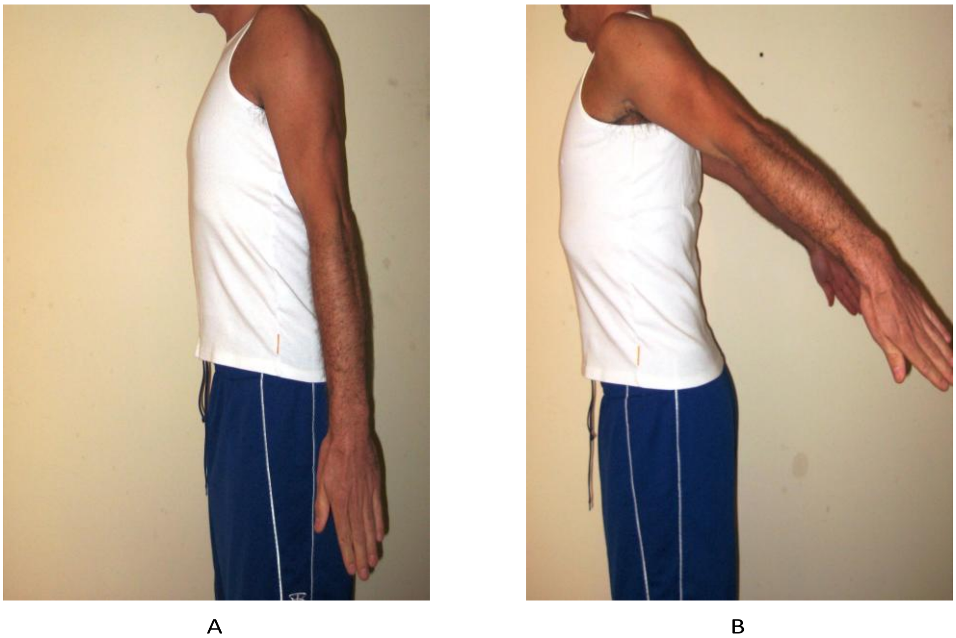


Figure 4.2 Arm start position for arm-swings during CMJ with (A, CMJCA) and without a countermovement (B, CMJNCA) (adapted from Hara et al., 2006).

Kinematic analyses

This study adopted the same kinematic and active range of motion methodologies as stated within the previous study and the reader is referred to Chapter 3.3 of this thesis.

Data processing

Angular kinematic and active range of motion data were processed in the same way as stated in the previous study (see Chapter 3). The comparative kinematic data for the CMJ performed with and without a countermovement arm-swing were analysed by phase, using key movement events throughout the trials (Figure 4.3), and overall time in each phase was collated as phase duration calculated relative to total jump duration for each jump. The events were listed as preparatory, maximum hyper-extension (shoulder), low-point (arms), horizontal point (arms) and take-off, which then determined the arm-swing phases, listed as 1, leg countermovement, 2, arm down-swing, 3, arm up-swing and 4, eccentric deceleration.

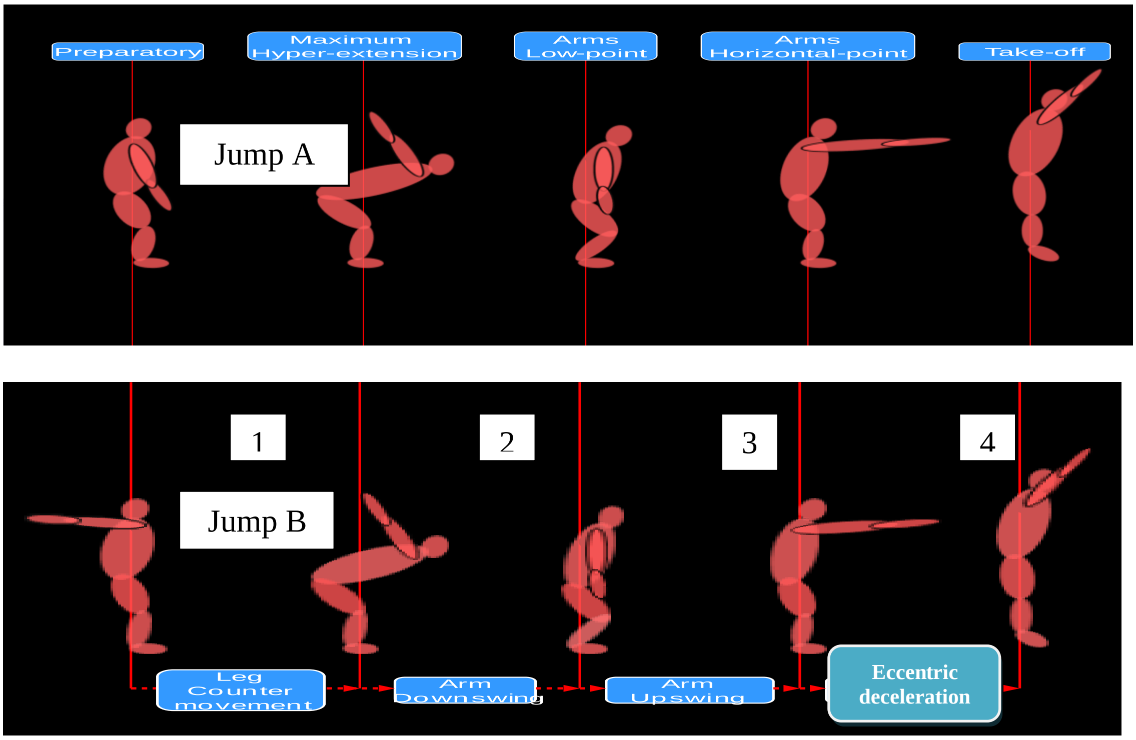


Figure 4.3 Four phases determining the key arm-swing events during CMJ performed with (Jump A) and without (Jump B) a countermovement arm-swing.

Statistical analyses

The kinematic data were exported into Microsoft Excel and descriptive statistics (mean ± SD) were calculated for joint ω, AROM and jump height. Only the peak trial and highest jump from each condition was used for analysis. Peak joint angular velocities were reported in relation to their sequence (proximal to distal), phase location (1 - 4) and the overall occurrence of each joint peak ω within each phase for all participants was expressed in percentage terms. The mean values of all the dependent variables were compared between jump types using paired samples *t*-tests, following confirmation of the normality of their distributions via the Shapiro-Wilk statistic. The alpha level was set at $P \leq 0.05$. Statistical analysis was carried out using SPSS v. 18.0.

4.4 Results

The descriptive statistics for CMJ performed with (CMJCA) and without a countermovement arm-swing (CMJNCA) are reported in Table 4.2. Importantly, peak ω at the shoulder occurred during different phases within the jump, occurring in Phase 2 in the CMJCA condition but later in Phase 3 in the CMJNCA condition. However, irrespective of the different phase in which peak ω at the shoulder occurred in the two jump conditions, the shoulder acted as the proximal rotating upper-body segment in the kinematic chain. The mean peak value in the shoulder was higher in the CMJCA condition. The peak ω for each distal segment to the shoulder occurred during Phase 4, with peak hip, knee and ankle ω following a pattern of lower body triple extension (hip→knee→ankle).

Table 4.2 Mean values (± SD) for peak ω and peak ω location (phase) during both CMJCA and CMJNCA.

	Jump Type			
	CMJCA		CMJNCA	
Joint	Peak ω ($deg \cdot s^{-1}$)	Phase	Peak ω ($deg \cdot s^{-1}$)	Phase
Ankle	986.7 ± 573.1	4	1300.1 ± 866.1	4
Knee	-956.9 ± 278.3	4	-1062.4 ± 449.6	4
Hip	620.8 ± 247.0	4	635.1 ± 222.6	4
Shoulder	748.3 ± 98.8*	2	680.8 ± 84.3	3
Elbow	492 ± 354.6	3	509.6 ± 346.6	4

* Significant differences between jump types ($p < 0.05$).

Peak ω: Mean (±SD) peak joint ω ($deg \cdot s^{-1}$).

Phase: location of the peak ω within Phases 1-4.

The between-jump comparisons revealed that the peak shoulder ω in the CMJCA condition (748.3 ± 98.8 $deg \cdot s^{-1}$) was significantly higher (t (18) = 4.1, $p = 0.001$) than the CMJNCA condition (680.8 ± 84.3 $deg \cdot s^{-1}$). No significant differences were found for the ankle, knee, hip and elbow joints. Importantly, the CMJCA yielded significantly higher jump height (t (18) = 4.8, $p < 0.001$) than the CMJNCA (see Table 4.3).

Table 4.3 Mean values (± SD) for maximum vertical displacement of hip marker during both CMJCA and CMJNCA.

	CMJCA	CMJNCA
Hip max (cm)	44.7 ± 6.5*	38.5 ± 8.6

* Significant differences between jump types ($p < 0.05$)

Hip max: maximum vertical displacement of hip marker.

The shorter total jump time observed in the CMJCA condition (Table 4.4) was reflected by a smaller percentage of time spent in the leg countermovement phase (≤ 0.05 s). A paired-samples t-test indicated that values were significantly higher for the percentage of time spent in the arm down-swing phase (Phase 2) during the CMJCA condition (34.7 ± 6.9%) than for the CMJNCA condition (29.2 ± 6.6%), t (18) = 3.5, $p = 0.003$, yet no significant differences were found for the actual time spent in the arm down-swing phase. Conversely, the actual time spent in the arm up-swing phase (Phase 3) during the CMJCA condition (0.0926 ± 0.01 s) was significantly shorter (t (18) = -2.2, $p = 0.04$) than for the CMJNCA condition (0.1032 ± 0.02 s).

Table 4.4 Mean values (± SD) for total jump time, time in each phase and percentage time in each phase (in respect to total jump time) during both CMJCA and CMJNCA.

	CMJCA		CMJNCA	
	Phase time (s)	%	Phase time (s)	%
Total time (s)	0.56 ± 0.12	100	0.59 ± 0.16	100
Leg c/movement (1)	0.18 ± 0.09	30.1 ± 9.5	0.23 ± 0.17	35.4 ± 14.4
Arm down-swing (2)	0.2 ± 0.06	34.7 ± 6.9*	0.17 ± 0.03	29.2 ± 6.6
Arm up-swing (3)	0.0926 ± 0.01*	17.0 ± 3.6	0.1032 ± 0.02	18.5 ± 5.2
Arm eccentric deceleration (4)	0.0979 ± 0.01	18.1 ± 4.5	0.0942 ± 0.04	16.8 ± 6.5

*significant differences between jump types ($p < 0.05$)

Total time: total time for jump time (preparation to take-off).

Phase time: time spent in each phase.

% Phase time: expressed relative to the total jump time.

The mean time spent during the arm deceleration phase (Phase 4) was similar for both jump conditions and were not significantly different (t (18) = 0.4, p = 0.68). However, whilst the percentage in time spent in the arm up-swing phase (Phase 3) of the CMJCA was less (17 ± 3.6%) than its arm deceleration phase (18.1 ± 4.5%), the opposite was observed for the CMJNCA (18.5 ± 5.2% and 16.8 ± 6.5% for Phases 3 and 4, respectively). The between-jump comparisons revealed that the utilised AROM in the CMJCA condition (56.3 ± 12.8 °) was significantly lower (t (18) = -7.3, p = 0.001) than the CMJNCA condition (67.8 ± 11.1 °). This was reflected by the significantly lower (t (18) = -7.1, p = 0.001) percentage difference (between available and utilised) AROM shown by the CMJCA condition (82.8 ± 10.5%) compared to the CMJNCA condition (99.9 ± 0.2%) (see Table 4.5).

Table 4.5 Mean values (± SD) for pre-test, utilised and percentage difference active range of motion (AROM) during both CMJCA and CMJNCA.

	CMJCA	CMJNCA
Pre-test AROM (°)	67.6 ± 10.9	67.6 ± 10.9
Utilised AROM (°)	56.3 ± 12.8*	67.8 ± 11.1
% Diff AROM	82.8 ± 10.5*	99.9 ± 0.2

*Significant differences between jump types ($p < 0.05$)

Pre-test AROM: maximum AROM at the shoulder (hyper-extension) prior to trials.

Utilised AROM: maximum AROM at the shoulder (hyper-extension) during trials.

% Diff AROM: percentage difference of utilised AROM.

Not surprisingly, no significant differences were found between the pre-test AROM (67.6 ± 10.9 °) and the utilised AROM (67.8 ± 11.1 °) in the CMJNCA condition, as maximum shoulder hyper-extension defined the start position of the arms during CMJNCA, however, utilised AROM (56.3 ± 12.8 °) was significantly lower (t (18) = 7.4, $p = 0.001$) than the pre-test AROM (67.6 ± 10.9 °) in the CMJCA condition.

Figure 4.4 highlights the position of peak shoulder ω (in relation to its occurrence in Phases 2 and 3), for the CMJCA condition (-0.008 s), with the purple (upper-arm) and light blue (forearm) segments plotted relative to their rotation around the dark blue (trunk) segment. The single solid digital trace shows peak shoulder ω occurred prior to the low-point of the arms, during the arm-downswing phase and is shown in pictorial view in the left-hand figure. The single dotted digital trace shows the location of the peak shoulder ω for the CMJNCA condition (0.028 s), occurring after the low-point of the arms, during the arm-upswing phase and is shown in pictorial view in the right-hand figure.

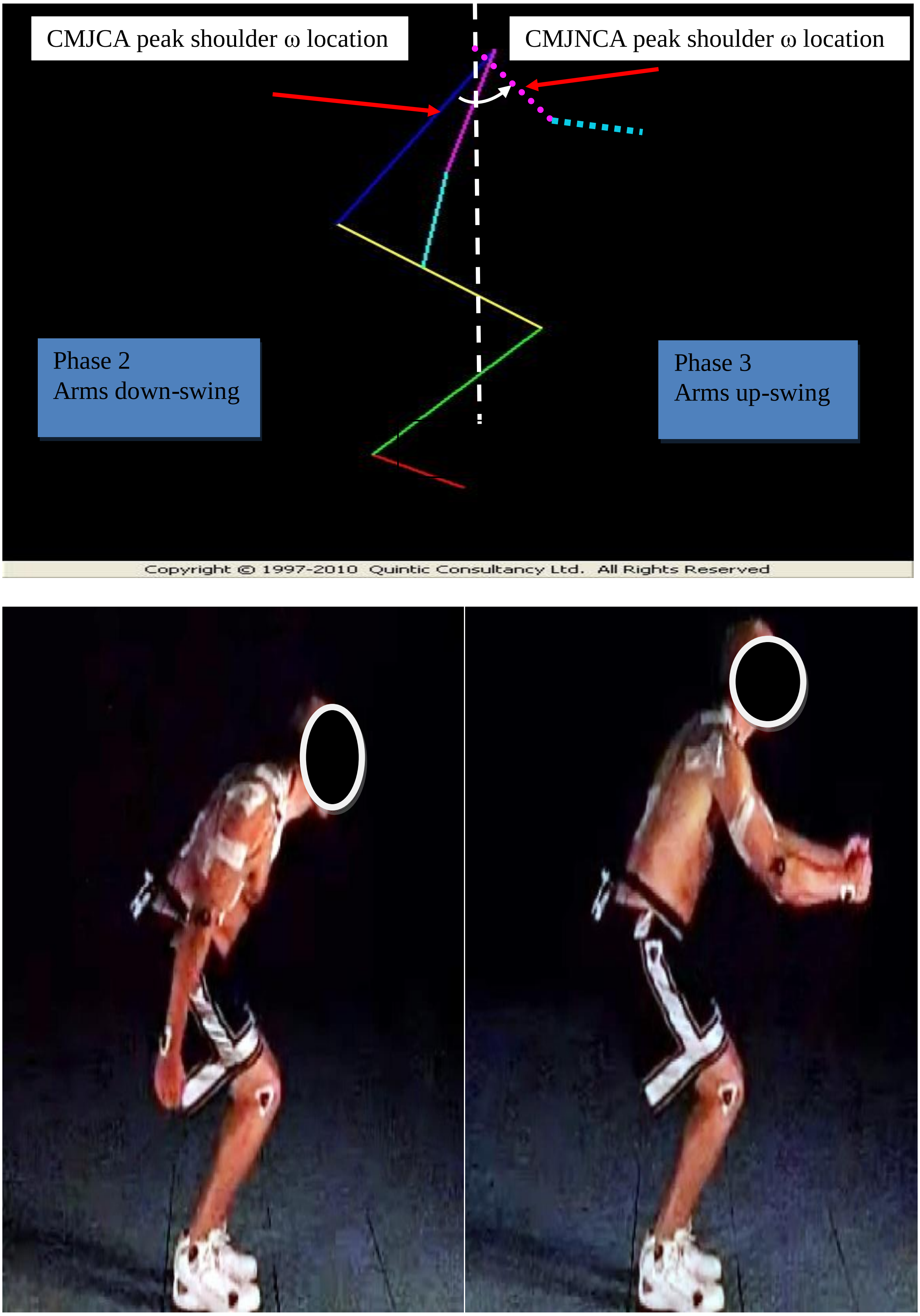


Figure 4.4 Location for the mean peak ω at the shoulder joint during the CMJCA condition (arm down-swing, -0.008 s) and during the CMJNCA condition (arm up-swing, 0.028 s)

The distribution of peak shoulder ω position values for all participants (relative to the low-point of the arms) is plotted in Figure 4.5. For 84.2% of the participants in the CMJCA condition peak shoulder ω occurred prior to the end of the arm down-swing, and the remainder into the arm up-swing phase, whereas in the CMJNCA condition, 100% of the participants' peak shoulder ω occurred during the arm up-swing phase. The mean peak shoulder ω position for each condition is indicated by the dotted blue (CMJCA = 0.028 s) and pink lines (CMJNCA = -0.008 s).

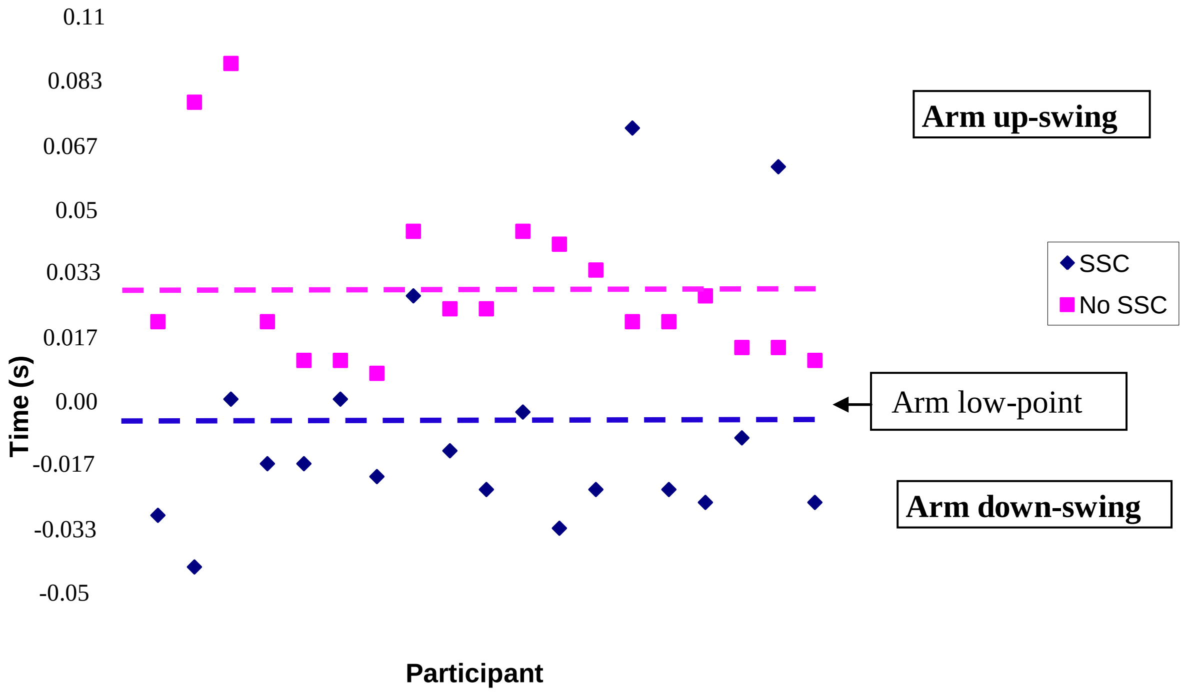


Figure 4.5 Location of individual peak shoulder ω values during CMJCA and CMJNCA. The dotted lines (Blue: CMJCA) indicate the mean peak shoulder ω position (Pink, CMJNCA = -0.008 s; Blue, SSC = 0.028 s).

4.5 Discussion

In conducting the first study to examine vertical jumps performed with (CMJCA) and without (CMJNCA) the contribution of an arm-swing countermovement, the current research confirmed the *a priori* hypotheses with respect to the key kinematic variables. That is, in relation to arm-swing kinematics, peak ω at the shoulder was significantly greater for CMJCA (748.3 ± 98.8 deg·s^{-1}) when compared to CMJNCA (680.8 ± 84.3 deg·s^{-1}), and this was reflected by a significantly quicker time spent during the arm up-swing phase (Phase 3, 0.0926 s) than in the CMJNCA condition (0.1032 s). There was a significant increase in jump height during CMJCA (44.7 ± 6.5 cm) compared to CMJNCA (38.5 ± 8.6 cm). Moreover, the amount of available AROM utilised during CMJCA (56.3 ± 12.8°) was significantly lower when no preceding arm-swing countermovement was used during CMJNCA (67.8 ± 11.1°). This was partly due to CMJNCA utilising an AROM (67.8 ± 11.1°) that was near to the maximum available (67.6 ± 10.9°), resulting in a significantly higher percentage difference (99.9 ± 0.2%) of AROM utilised than CMJCA (82.8 ± 10.5%).

The observed increase in peak shoulder ω during CMJCA, that is, when using an arm-swing countermovement, is consistent with previous studies that have shown an increase in upper-extremity kinematics when utilising a countermovement (Newton et al., 1997; Doan et al., 2002; Miyaguchi et al., 2008; Miyamoto et al., 2010). The increase in peak shoulder ω (+10%) in the current study is comparable to the findings reported by Miyaguchi et al. (2008), who observed a 17% increase in muscle strength during countermovement elbow flexion when compared to a concentric only movement. The increase in muscle strength resulted from a combined increase in initial concentric arm velocity (+0.18 m.s^{-1}) and overall peak arm swing velocity (+0.04 m.s^{-1}). The increase in both the initial and peak arm-swing velocity was attributed to the utilisation of the SSC during the countermovement condition, indicating that an increase in muscle pre-stretch during countermovement elbow flexion yielded greater concentric phase performance. This idea is confirmed by the increase in initial concentric arm velocity (+0.18 m.s^{-1}) being greater than the increase observed in overall peak arm swing velocity (+0.04 m.s^{-1}), suggesting that the use of a preceding countermovement prior to concentric performance is important for developing muscle force in the initial phase of the subsequent concentric contraction, and not for overall concentric performance. This agrees with previous SSC studies that have shown an increase in concentric performance immediately following eccentric concentric coupling (e-c coupling), attributing this to both an increase in the active muscle state (Bobbert et al., 1996; Bobbert et al., 2005) and the subsequent faster potentiation of the contractile components (Binder-McCleod et al., 2002), as well as increased use of the stretch reflex system (Gollhofer et al., 1992; Komi et al., 1997; Nicol et al., 2006; Gerodimos et al., 2008) and the effective storage and utilisation of elastic energy (Kubo et al., 1999; Lees et al., 2004; Havalee et al., 2005; McBride et al., 2008).

Additionally, it takes time to develop force in a muscle (Bobbert et al., 1996), therefore, when a decrease in segment velocity is present during the initial concentric phase in a concentric only movement, as observed in concentric only elbow flexion (-0.18 m.s^{-1}) (Miyaguchi et al., 2008), it suggests an initial period of sub-maximal concentric force, ultimately leading to a delay in the achievement of peak segment velocity. The findings in the current study agree with this suggestion, as both concentric peak shoulder ω (- 68 deg·s^{-1}) and the time to peak shoulder ω was achieved (+ 0.036 s) were reduced during CMJNCA, indicating that the use of a preceding countermovement during CMJCA enhances the use of the SSC and leads to an increase in the subsequent concentric phase (arm down-swing phase). This was further shown in a study examining ballistic bench throws with (SSC) and without a countermovement, demonstrating an increase in average concentric velocity, average force and peak force during the SSC condition (Newton et al., 1997).

Newton et al. (1997) showed increases in concentric performance similar to that of the current study, and suggested this was dependent upon the utilisation of the SSC and the stretch reflex systems, demonstrating significantly greater EMG activity in the pectoralis major and triceps brachii during the initial 100 ms of the concentric phase in the SSC condition. This suggests movements preceded by a countermovement such as the arm-swing during CMJCA, develop a greater muscle active state than in concentric only movements (CMJCNA), and this leads to a greater force developed in the muscle at the initial onset of the concentric phase (Bobbert et al., 1996; Takarada et al., 1997; Komi, 2000; McBride et al., 2008). Moreover, this reflects greater SSC utilisation following the increase in eccentric muscle activity, actively developing pre-stretch in the agonist (prime mover) muscle responsible for the subsequent concentric performance (Cavagna et al., 1971; Bosco, 1997; Ingen Schenau et al., 1997). Stretch-shortening cycle utilisation during countermovement's can be demonstrated by the amount of eccentric braking force utilised by the muscles, as Newton et al. (1997) suggested the resulting increase in concentric performance following a countermovement was only apparent in the very early section of the concentric phase, and any enhancement from the SSC diminished after this, resulting in no significant difference in throw height.

With respect to vertical jumping, the significant increase in the forward motion of the arm-swing when using an arm-swing countermovement, occurred in the early section of Phase 2 (arm down-swing). This has been previously highlighted as the most important phase for increasing, energy transfer (Lees et al., 2004; Lees et al., 2006), segment rotation (Vanezis et al., 2005; Hara et al., 2006; Vanrenterghem et al., 2008) and initiation of the proximal to distal sequence of joint extension (Ashby et al., 2002; Hara et al., 2006; Hara et al., 2008). Moreover, if these jump mechanisms require peak concentric performance of the arms during Phase 2, then it could be argued that this is also a primary requirement for increasing jump height, as an increase in energy transfer, segment rotation and the initiation of the proximal to distal sequence of joint extension have all been shown to indirectly increase jump height.

The increase in jump kinematics resulting from the utilisation of an arm-swing countermovement highlights the importance of understanding the full arm-swing kinematics, and not just their contribution during the leg propulsion phase as previously examined (Feltner et al., 1999; Feltner et al., 2004; Lees et al., 2006; Hara et al., 2006). This can also be observed when examining the time differences in the jump phases, as any small decrease spent in an early jump phase can lead to an increase and enhanced jump kinematics in the later jump phases. The time differences spent in each phase of the jump may offer evidence to support this suggestion, demonstrated mainly by a significantly shorter time spent in the arm up-swing phase during CMJCA (0.0926 s) when compared to CMJNCA (0.1032 ± 0.02 s). This would have resulted from the increase in peak shoulder ω occurring in the previous arm down-swing phase. Conversely, during CMJNCA the participant's peak shoulder ω was not observed until later on during the arm up-swing phase, therefore, the time spent in this phase was significantly longer in the CMJNCA condition. This finding can be explained by the reduction in concentric performance in the early stage of arm down-swing phase during CMJNCA, suggesting that the arm-swing took longer to reach peak ω (Bobbert et al., 1996; Binder-McCleod et al., 2002). Furthermore, this trend would indicate the arms travelled faster at the start of the arm up-swing phase in the CMJCA condition, which would ultimately lead to a decrease in time in that phase. A decrease in the arm up-swing phase indicates a positive impact on jump kinematics, as here the body starts to initiate lower-extremity propulsion, as the COM is now driven in an upward direction by the leg muscles, and a shorter time period in this phase suggests leg propulsion is now also acting faster during CMJCA (Feltner et al., 2004; Hara et al., 2006; Lees et al., 2006).

The time spent during each jump phase might have resulted directly from the amount of utilised AROM at the shoulder, however, between-jump comparisons revealed that the utilised AROM in the CMJCA condition (56.3 ± 12.8 °) was significantly lower than the

CMJNCA condition (67.8 ± 11.1 °). Notably, the marked decrease in utilised AROM during the CMJCA condition coupled with an increase in peak shoulder ω suggests that the use of a preceding countermovement during CMJCA results in the participant's increased ability to produce concentric muscle force in a shorter time period and with less utilised AROM. Conversely, the observed increase in utilised AROM during CMJNCA did not result in a further increase in arm-swing ω when compared to CMJCA, and peak shoulder ω did not occur until the arm up-swing phase, indicating that the use of a countermovement coupled with a reduced amount of utilised AROM is more beneficial to the arm-swing mechanics than increasing the amount of available AROM utilised during CMJNCA. However, the CMJCA group only utilised 82.8% of their available maximum AROM, suggesting there may be an optimal amount of AROM that should be used before a negative impact is observed. This might suggest that the muscles' stretch reflex response to the active pre-stretch in the muscle during the countermovement (Ingen Schenau et al., 1997a; Hamill & Knutzen, 2010), as the amount of utilised AROM during the arm-swing countermovement will define the amount of alpha motor neuron activity that is increased (Nicol et al., 2006; Komi et al., 1997).

As alpha motor neuron activity increases, the use of the stretch reflex also increases, suggesting an increase in the speed of the participants' arm-swing countermovement would increase their ability to facilitate the full potential of the stretch reflex system (Gollhofer et al., 1992; Nicol et al., 2006; McBride et al., 2008). However, if the rate or magnitude of muscle stretch during the arm-swing countermovement is too large, an opposing inhibitory mechanism reacting to excessive muscle stretch occurs. That is, the golgi tendon organ (GTO) in the same muscle exhibiting high level pre-stretch will induce muscle relaxation (Komi et al., 1997; Ingen Schenau et al., 1997a). This may be why the participants in the CMJCA condition only utilised 82.8% of their available maximum AROM, yielding an effective use of the SSC system without an increase in GTO activation. Similar findings have been examined in the lower-extremities, as increased stretch reflex facilitation during DJ from increasing drop heights demonstrated a positive impact upon jump height up to a drop height of 60 cm, However, once this drop height exceeded 60 cm (DJ-80 cm), stretch reflex facilitation was reduced, mainly due to the increase in GTO activation (Komi et al., 1997). Interestingly, the evidence suggests there could be an optimal condition for countermovement’s to facilitate maximal use of the stretch reflex system, yet this has never been examined empirically for the upper-extremities (Komi et al., 1997; Moran et al., 2007). Furthermore, the arm-swing countermovement may demonstrate a similar trend in stretch reflex utilisation as the lower-extremities, and this warrants further investigation. It is suggested that future arm-swing studies in vertical jumping should attempt to identify the amount of AROM that is optimal for increasing arm-swing kinematics, which may possibly redefine the way in which athletes’ train the upper-extremities.

The decrease in the amount of utilised AROM in the CMJCA condition (- 82.8 ± 10.5%) was expected to be reflected by shorter jump phase durations during the arm down-swing phase; however this was not found in the current study (+ 0.03 s). Furthermore, a significant increase was observed in the percentage of time spent in the arm down-swing phase during CMJCA (+ 5.5%), and this was unexpected as a decrease in utilised AROM (as shown during CMJCA) should have resulted in a decrease in arm down-swing time. A possible explanation for this could be the definition of the arm down-swing phase start position in each jump condition, that is, the actual time when the arm-down-swing began. During CMJNCA, the arm-swing countermovement was isolated (held in maximum hyper-extension) prior to the start of the jump (Hara et al., 2006) and in an attempt to keep the leg countermovement exactly the same during both jump conditions (Feltner et al., 2004), the arms did not start their swing until the upper body had lowered (trunk rotation). In effect, this kept the jump mechanics the same for both jump conditions, and resulted in the arm-swing and leg countermovement occurring at the same time in both conditions. However, the start position for the arm down-swing phase during CMJNCA was selected at the point the trunk started to rotate, and not the point at which the arms began their down-swing. This is a limitation to the current study and reflects the complexity of attempting to analyse a single movement that is located within a kinematic chain, that is, a movement that is normally not isolated during its normal mechanical movement. Future studies could aim to address this problem by initiating the start position for the arm down-swing phase at the point at which the arms actually start to rotate.

A further unexpected finding among the jump phase times was observed during the arm down-swing phase, as the percentage time spent in this phase was significantly higher (34.7 ± 6.9%) during the CMJCA condition when compared to CMJNCA (29.2 ± 6.6%), yet the actual time spent in this phase was not significantly different. This could be reflected by the jump phase time only representing the specific time spent in each phase with no reference to the whole jump time. Evidence for this suggestion might be apparent in the difference between jump times, and even though these were not significantly different, the mean jump time in the CMJNCA condition was 0.03 s longer. Importantly, the CMJCA achieved a significantly larger jump height (6.2 cm) with only a small decrease in time (0.0126 s), highlighting that the speed of the arm-swing can have a large impact on the jump kinematics.

An increase in peak shoulder ω during the early stage of the concentric performance, subsequent to the arm-swing countermovement (arm down-swing phase), effectively means the arms are swinging faster during the optimal phase for when the arms have the greatest positive impact upon jump height, as previously shown in the Chapters 3.5 and 3.6 of this thesis. Notably, this suggests that the arm-swing countermovement ensures that peak shoulder ω occurs prior to the arm-swing low point (-0.008 s), as this has been demonstrated to be the most important section of the jump phases for increasing the transfer of KE from the upper to lower-extremities (Lees et al., 2004; Lees et al., 2006), and increasing rotation of the trunk segment (Vanrenterghem et al., 2008). Conversely, performing CMJ with no arm-swing countermovement resulted in a peak shoulder ω occurring later in the arm up-swing phase (+ 0.028 s), suggesting that the transfer of KE from the upper to lower-extremities and the increase in rotation of the trunk segment would have occurred too late, meaning at the important arm-swing low point, these mechanisms were acting sub-maximally in the CMJNCA condition.

Moreover, any additional increase in shoulder ω during the arm down-swing phase will result in further increases in jump height, suggesting that training the arms to perform better during this phase (Phase 2) is essential to athletes whose primary aim is to increase vertical jump height. The overall change in the location of where peak shoulder ω occurs demonstrates how the arm-swing countermovement helps peak shoulder ω occur faster and during the arm down-swing phase. Interestingly, the current research examining upper-extremity countermovements indicates that concentric performance is directly affected by the preceding phase, that is, the correct utilisation of a countermovement and the associated SSC mechanisms. Applied to vertical jumps, this will lead to an increase in the arm down-swing movement, and a subsequent increase in jump height. The primary suggested training method for such movements involving coupled countermovement's and increased concentric performance is plyometric type exercises (Villarreal et al., 2009a), as these effectively increase the athlete's ability to utilise the SSC during countermovements. These plyometric type exercises have been shown to improve the SSC in the lower-extremities, but have never been empirically examined for their use in the upper-extremities during jumping. Furthermore, future studies should aim to develop plyometric exercises that improve all aspects of Phase 2 and Phase 3 of the arm-swing during CMJCA, and these exercises should be movement-specific to ensure they target only the muscles used during the arm-swing.

4.6 Conclusion

The primary aim of this study was to examine vertical jumps performed with and without arm-swing countermovement; therefore, identifying the contribution of the stretch-shortening cycle (SSC) within the arm-swing countermovement during maximal countermovement vertical jumps (CMJ). The main findings show that jumps performed with an arm-swing countermovement significantly increased mean jump height (+ 6.2 cm) and mean peak shoulder ω (+ 67.5 deg$^{\cdot s-1}$), therefore, it was evident that the arm-swing countermovement made a significant contribution to vertical jump performance. A contributing factor to the increase in jump height was the location of peak shoulder ω, as the use of an arm-swing countermovement resulted in a faster time in which peak shoulder ω was achieved, therefore, enabling peak shoulder velocity to occur during the important down-swing phase of the arm-swing. In contrast, the peak ω during the no arm-swing countermovement condition occurred during the upswing phase, which was highlighted by the significantly shorter time spent in the arm up-swing phase during arm-swing countermovement condition (0.0926 s) when compared to no arm-swing countermovement (0.1032 ± 0.02 s). Therefore, the use of an arm-swing countermovement typically caused a significantly greater peak shoulder ω (+68 deg·s^{-1}) with a quicker time to peak (- 0.036 s), and this led directly to a significant increase in jump height (+6.2 cm) when compared to the jumps performed with no arm-swing countermovement. The observed increase in shoulder ω and subsequent increase in jump height during the arm-swing countermovement was attributed to the participants' ability to utilise the SSC during the eccentric phase of the arm-swing countermovement, which led to an increase in the transfer of elastic energy, development of a higher muscle active state, greater facilitation of the stretch reflex system and better use of the muscle contractile components (Komi et al., 1997; Bobbert et al., 2005; McBride et al., 2008; Gerodimos et al., 2008; Hara et al., 2008), and an overall increase in concentric performance.

CHAPTER 5

AN INVESTIGATION INTO THE EFFECTS OF A 4-WEEK UPPER-EXTREMITY PLYOMETRIC INTERVENTION ON VERTICAL JUMP PERFORMANCE IN NATIONAL LEAGUE LEVEL MALE BASKETBALL PLAYERS

5.1 Abstract

The aim of this two-part study was to examine the use of upper-extremity plyometrics as a training modality for improving arm-swing kinematics during vertical jumping, as well assessing their suitability for increasing jump height. Part 1 of the study aimed to establish the optimal conditions for the arm-swing during vertical jumping, whilst Part 2 examined the use of an upper-extremity plyometric programme for increasing vertical jump height. Twenty male participants (age 20.3 ± 1.3 y; stature 1.80 ± 0.06 m; body mass 75.4 ± 9.4 kg) who were currently active National League basketball players and free of injury, volunteered to participate in the study. Separate twelve-segment and five-segment biomechanical models were defined using 65 and 35 reflective markers respectively, placed on anatomical landmarks and full body kinematics were captured using a 3D motion capture system. Each participant performed three CMJ, followed by a batch of 32 varied arm-swings whilst sitting securely in a modified chair. Each participant was then randomly assigned into either an experimental (4-week upper-extremity plyometric intervention) or control group (no plyometrics). The key findings from Part 1 in this study revealed that the use of a large arm back-swing (67° 90° large or 84° 90° large) during vertical jumping was the best condition for achieving the greatest peak shoulder ω (622 and 606 deg·s^{-1}, respectively). The key findings from Part 2 in this study revealed that the use of an upper-extremity plyometric training programme significantly increased the mean jump height (+ 7.2 cm), mean peak shoulder ω (+ 167.1 deg·s^{-1}), mean peak frontal shoulder ω (+ 121 deg·s^{-1}) and mean AROM at the shoulder joint (+ 5.3 °), when compared to a control group. The findings suggest that the athletes increased their ability to use the SSC during the post-test vertical jumps, and therefore, the use of upper-extremity plyometrics to increase vertical jump performance should be advocated.

5.2 Part 1: Introduction

The larger jump heights observed in CMJ when compared to SJ are explained by several potential mechanisms occurring in the lower-extremities. These mechanisms include: increases in the active muscle state (Bobbert et al., 1996; Bobbert et al., 2005), potentiation of the contractile components (Binder-McCleod et al., 2002), the stretch reflex system (Komi & Gollhofer, 1997; Gerodimos et al., 2008) and the effective storage and utilisation of elastic energy (Bobbert et al., 1996; McBride et al., 2008) (For a detailed description of these, the reader is referred to Chapter 2 of this thesis). The uniting factor is that all these mechanisms utilise positive attributes achieved during an eccentric muscle action, which in turn, helps improve the subsequent concentric action in SSC type movements. Furthermore, investigators have shown that as eccentric loading of the muscle increases, further improvements are observed in the following concentric action. Overall, this has resulted in a better understanding of the relationship between eccentric and subsequent concentric muscle actions in the lower-extremities (Moran et al., 2007). However, SSC type movements in the upper-extremities have not been examined in as much detail and this requires further investigation.

When upper-extremity movements are preceded by a countermovement (such as the arm-swing in vertical jumping) the subsequent concentric movement should show similar improvements to those observed in the lower-body. Nonetheless, until recently the countermovement within the arm-swing during vertical jumping was not fully explored. Notably, the previous chapter in this thesis (see Chapters 4.5 and 4.6) conducted a comparative study of countermovement jumps performed with and without an arm-swing countermovement, and highlighted that an increase in both mean jump height (6.2 ± 2.1 cm) and mean peak shoulder ω (68 ± 14.5 deg·s^{-1}) were achieved during the arm-swing countermovement condition. Arguably, this suggests that as the level of countermovement increases (eccentric loading), the subsequent concentric movement will further increase.

Increasing the amount of eccentric loading in the lower-extremities during vertical jumping has been shown to have a positive effect upon vertical jump performance (Moran et al., 2007; Gerodimos et al., 2008). Therefore, it is possible that increasing the eccentric load available during the arm-swing countermovement will yield similar positive results in concentric arm-swing kinematics. Furthermore, increases in peak shoulder ω and AROM utilised by the shoulder during the arm-swing countermovement condition, have both been shown to significantly increase jump height (see Chapters 4.5 and 4.6 in this thesis). However, the exact determinant for how much AROM should be used during a countermovement has not been fully explored and warrants further investigation.

Vertical jumps performed with either an increase in the speed (an exaggerated starting position, such as greater drop height) or magnitude (an exaggerated finishing position, such as a greater use of lower-extremity AROM) of countermovement, were examined by Moran et al. (2007) in an attempt to identify how much eccentric load is best for achieving peak concentric performance of the lower-extremities during vertical jumping. Moran et al. (2007) found that a combined increase in both the speed and magnitude of lower-extremity countermovement was most favourable for increasing jump height (Moran et al. 2007). In relation to the amount of countermovement magnitude, a similar finding was observed in Chapter 4.5 of this thesis, as an increase in the magnitude of arm-swing countermovement resulted in increased concentric performance of the overall arm-swing. However, the various types of eccentric load examined by Moran et al. (2007) for the lower-extremities have never been measured for the upper-extremities (am-swing) during vertical jumping. Furthermore, if the concentric performance of the arm-swing can be improved by identifying better arm-swing countermovement conditions, then this warrants further examination. Therefore, the aim to part one of this study was to examine a range of arm-swing countermovement conditions (providing various amounts of eccentric load), in order to highlight which condition is best for improving the arm-swing. It was hypothesised that:

1. Peak shoulder ω during the arm-swing trials will be greatest in the arm-swings with the largest amount of eccentric load.
2. Peak shoulder ω during the arm-swing trials will be greatest with the largest amount of trunk flexion.
3. Peak shoulder ω will be the highest in the arm-swing trials with the greatest amount of AROM available.
4. Peak shoulder ω will increase in the large AROM arm swings following four weeks of plyometric training.

5.3 Part 1: Methods

Participants

Twenty male participants (age 20.3 ± 1.3 y; stature 1.80 ± 0.06 m; mass 75.4 ± 9.4 kg) who were active National League basketball players and free of injury, volunteered to participate in the study. Each participant provided written informed consent (Appendix 5.31) to participate and completed a pre-test health questionnaire prior to testing (Appendix 5.32). The study was approved by the University of Chester's Faculty of Applied Sciences Research Ethics Committee (Appendix 5.33).

Study design

The study involved an experimental design with repeated measures in which participants where randomly assigned to either an experimental group (n = 10) or control group (n = 10). Both groups completed 32 countermovement arm-swings in a secure chair 72 hours after a habituation session that allowed each participant to experience each individual variation of arm-swing trial. The participants were instructed to perform each arm-swing as fast as possible and were not given any performance-related feedback. Upper-extremity kinematics collated from a 3D motion capture system were recorded for data analyses. Upon completion of all the baseline arm-swing measurements, the participants in the experimental group were required to complete a four week upper-extremity plyometric intervention (see Chapter 5: Part 2), whilst the control group were instructed to continue in their normal sporting activities. Upon completion of the intervention, the arm-swing measurements were performed by both groups for a second time, 72 hours post-intervention (see Figure 5.1). The key dependent variables obtained from kinematic analyses were peak shoulder ω in three planes of motion (3D), and peak active range of motion.

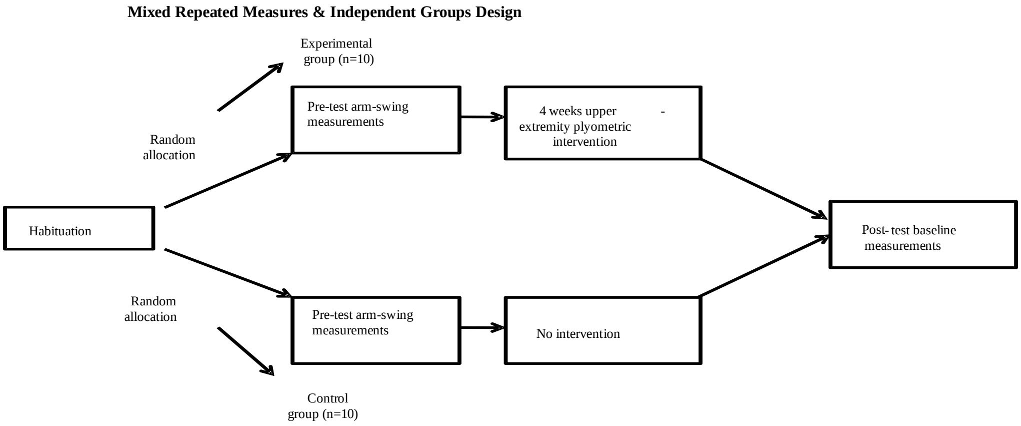


Figure 5.1 Schematic of study timeline

Pre-test procedures

Warm- up protocol

Sub-maximal plyometric arm-swings were performed to warm up the upper-extremities in preparation for the arm-swing trials (Carter et al., 2007). The participants used low resistance elastic bands (Theraband, Golds Gym, USA) located in two separate angled starting positions (see Figure 5.2) to perform two sets of 15 repetitions of arm-swing flexion, followed by arm-swing extension.


[redacted]

Low angle High angle

Figure 5.2 Sub-maximal arm-swing plyometric exercise in two angled start positions

Custom built chair (countermovement arm-swings)

To analyse the countermovement arm-swing in various start and finish positions and then measure arm-swing kinematics in isolation, it was necessary to create a system to secure all other body segments into a locked position. A weight-training bench was modified and enabled participants to sit in a secured squat-like position, as if at the bottom of the propulsion phase of a jump (Figure 5.3).

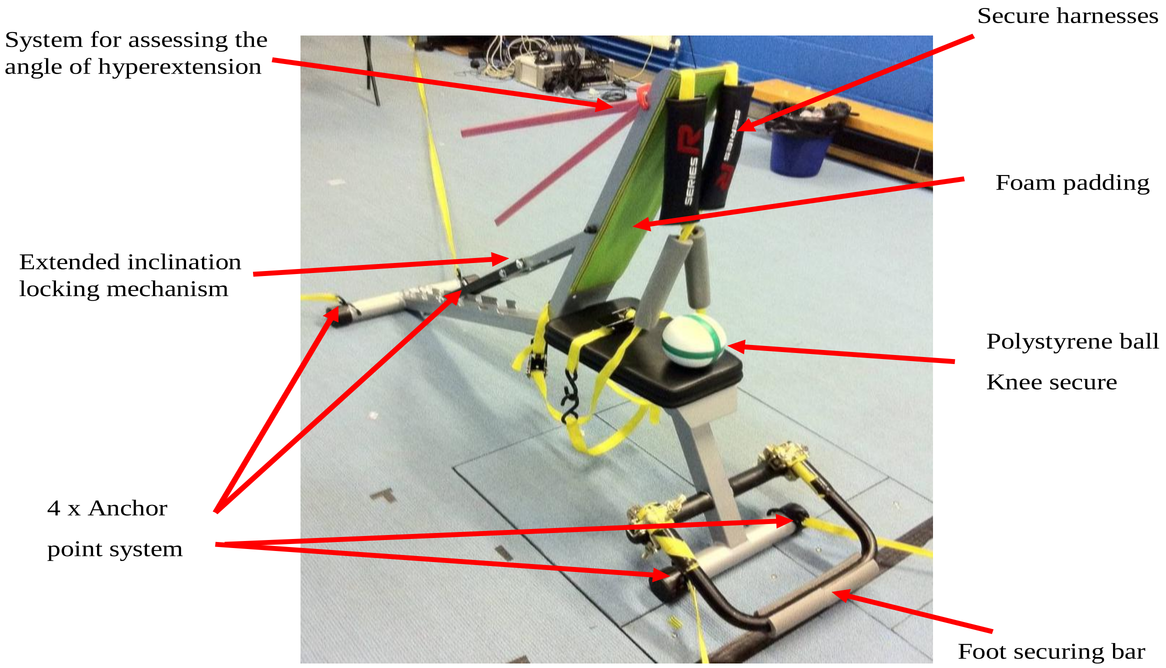


Figure 5.3 Modified weight-training bench

Countermovement arm-swings

Participants were strapped into the custom built chair (see Figure 5.3) and baseline measurements were recorded for both their preferred choice of arm-swing starting position and concentric-only (arms start at maximum shoulder hyper-extension; no countermovement) arm-swing start position. Countermovement arm-swings were measured in respect of (i) three variations of range of motion (AROM), (ii) two variations of trunk inclination position and

(iii) two variations of arm-swing start position (eccentric load). The amount of countermovement arm-swing AROM to be utilised was determined as a percentage of each participant’s maximum shoulder hyperextension and measured using a goniometer (Baseline, USA) (0 to 33% (short AROM back-swing), 33 to 66% (medium AROM back-swing), and 66 to 100% (large AROM back-swing)). Achieving the desired amount of arm-swing AROM in each trial was assessed by monitoring three high-visibility reference poles clamped to the side of the chair’s back plate protruding backwards along the sagittal plane and ensuring each arm-swing landed in the correct percentage category (see system for assessing angle of hyper-extension in Figure 5.3).

The two variations of trunk inclination were determined from the previous study’s (Chapter 4) maximum trunk inclination values, and by calculating the median and upper quartile values (67° and 84°). Also, two variations of arm-swing start position were examined, which contributed to the variation in the magnitude of the arm-swing countermovement to be utilised in each trial, starting with the arm positioned in shoulder flexion (45° and 90°) and held for 2 s, before initiating the back-swing of the arms to the desired amount of shoulder hyperextension. Each arm-swing variation was measured against all the other variations, with each type of combination of trial between arm-swing start position (45° and 90°) and arm-swing countermovement position (short, medium and large) randomised in sets of six trials between the 67° trunk inclination position (67-45-short, 67-45-medium, 67-45-large, 67-90-short, 67-90-medium, and 67-90-large) and the 84° trunk inclination position (84-45-short, 84-45-medium, 84-45-large, 84-90-short, 84-90-medium, and 84-90-large). After the six randomised trials, a concentric only arm-swing and the participant’s own choice of arm-swing was performed, making a total of eight trials in each set before the participant was unstrapped from the chair and had five minutes rest whilst the next chair position was performed. The overall order that the trials were presented to each participant was randomised, but each participant performed their own arm-swing trials in the same order in both pre and post-test arm-swing measurements. Each trial was performed maximally with 60 s rest between individual arm-swing trials.

Three dimensional high-speed kinematic analyses

Arm-swing kinematics were captured using a 3D motion capture system, comprising 7 ProReflex MCU high speed cameras (Qualisys, 240 Hz, Sweden) (Figure 5.4).

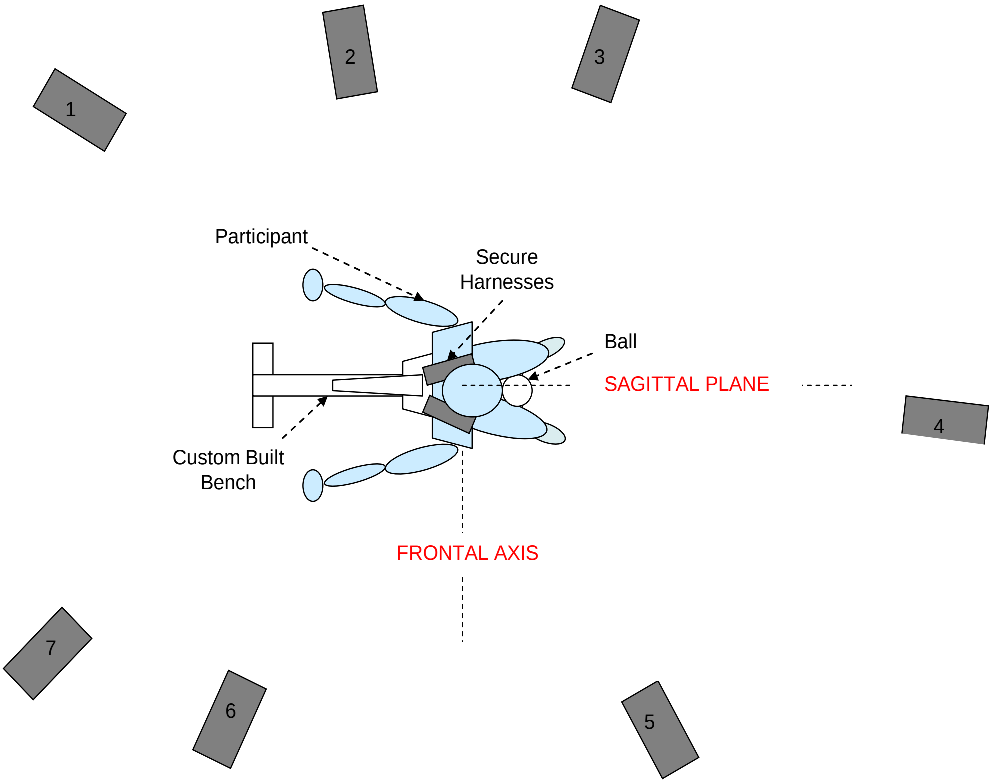


Figure 5.4 Laboratory set-up

Reflective spherical markers (15 mm; Qualysis, Sweden) were placed on 35 anatomical landmarks (*n* = 35 for calibration, *n* = 15 for anatomical, *n* = 23 for tracking) (Figure 5.5), on both sides of the body to define a five-segment biomechanical model to be used for the arm-swing trials (Lloyd, Alderson & Elliott, 2000; Wu et al., 2005; Roca et al. 2006; Roca et al., 2007; Chin et al., 2009). The performance area was calibrated prior to testing using a calibration frame and a calibration wand, after which a standing calibration of each participant with their arms in the anatomical position was conducted. Once the calibration was checked and deemed appropriate for model building, fifteen of the anatomical markers were removed in preparation for the trials and the warm-up protocol was performed.

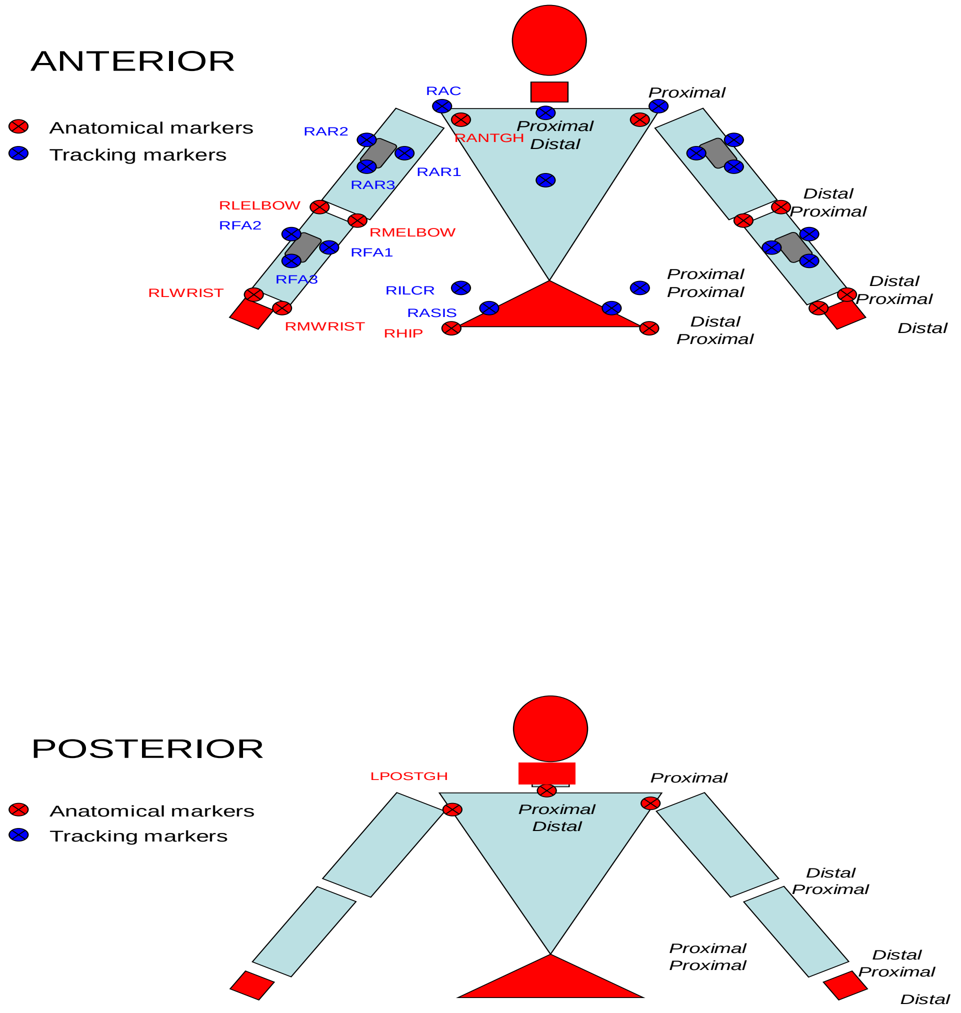


Figure 5.5 Five-segment biomechanical model (blue segments) defined by 35 anatomical landmarks (blue and red markers) (adapted from Lloyd et al., 2004; Lees et al., 2004; Wu et al., 2005).

Biomechanical model

A multi-planar 3D biomechanical model was developed in respect to the location of the gleno-humeral joint of the shoulder complex. Upper extremity 3D modelling remains underdeveloped for use within analysing sports performance, therefore it was necessary to develop a marker set and modelling system for the upper body using the extensive research undertaken in cricket bowling (Lloyd et al., 2000; Roca et al., 2006; Roca et al., 2007; Elliott & Alderson, 2007) coupled with the recommendations of the International Society of Biomechanics (ISM). A five-segment upper-body biomechanical model was developed and adapted using the University of Western Australia (UWA) marker set (Lloyd et al., 2000) and the trunk segment was orientated in a distal to proximal order from the left and right anterior superior iliac spines to the right and left and acromioclavicular joints (Figure 5.6).

Figure 5.6 Upper-body biomechanical model adapted from the UWA marker set (Lloyd et al., 2000).

The gleno-humeral joint centre was defined using the UWA three marker shoulder triangulation system (shoulder triad comprised of anterior, posterior and acromioclavicular joint markers), defined by the point at which the bilateral intersection (abduction/adduction) between the anterior and posterior shoulder markers and the vertical drop-down point from the acromioclavicular joint (Figure 5.7), and a virtual space landmark was developed using visual 3D software.

Figure 5.7 Estimation of the gleno-humeral joint centre using the shoulder triad method (Lloyd et al., 2000) and key anatomical markers (RLELBOW, right lateral elbow; RMELBOW, right medial elbow; RPOSTGH, right posterior gleno-humeral; RANTGH, right anterior gleno-humeral; and the AC, acromioclavicular).

The radius of each participant's shoulder complex was built individually for both the left and right sides of the biomechanical model, defining the gleno-humeral joint centre as an axial off-set of 0.5 (50%) of the radius between the anterior and posterior shoulder markers. The orientation of the upper arm segment was then defined by the medial and lateral elbow markers, and the rotation of the gleno-humeral joint centre in relation to the acromioclavicular joint. Upon completion of the 3D model building, the static calibration files collated were assigned to the movement trials, and the local coordinate system for each model was checked against the global coordinate system.

Active range of motion (AROM)

The range of motion was measured during an active movement of shoulder hyper-extension, with the participant standing in the anatomical position. A universal goniometer (Baseline, USA) was used to assess the uni-axial rotation of the gleno-humeral joint in the sagittal plane. The angle was measured for the upper-arm segment in reference to rotation around the trunk segment, with the rest of the shoulder stabilised. The start position was at 90 degrees perpendicular to the horizontal (floor) line with the forearms positioned in a neutral position (thumbs in anterior aspect). The active range of motion (AROM) during the arm-swing trials was measured using the angular data for the shoulder joint, defined by the proximal (elbow) and distal joint (hip) markers, and analysed in Visual 3D software (C-Motion v1.02).

Data processing

Data for the performance trials were tracked using Qualysis Track Manager (QTM) and processed using Visual 3D (C-Motion v1.02), with angular kinematics calculated by the orientation for each joint centre and defined by the proximal segment rotation in reference to its distal (as reversed in Visual 3D software). The data were processed using the Visual 3D pipeline and upper body and lower body script files were developed, and smoothed using a Butterworth 4th order zero lag filter at 12 Hz (Lees et al., 2004).

Statistical analyses

The kinematic data were transferred into Microsoft Excel, and descriptive statistics (mean ± SD) were calculated for joint ω (peak concentric), angular displacement and peak shoulder AROM during each arm-swing trial. Diagnostic tests on the distribution of the kinematic variables were conducted via the Shapiro-Wilk (normality) and Levene test (homogeneity of variance), and were found to yield satisfactory outcomes. Firstly, as both the experimental and control groups baseline arm-swing data were the same prior to the upper-extremity plyometric intervention, the different arm-swing conditions were compared using paired sample *t*-tests for the overall sample with the alpha level set at $P \leq 0.05$, and each arm-swing condition was rank ordered in respect to peak shoulder ω (high to low). Additionally, as both the experimental and control groups post intervention results were different, the variability of the sample's kinematic results were assessed using separate two-way (group and trials) analysis of variance with repeated measures (ANOVA). The assumption of sphericity for each test was analysed using the Mauchly test, and adjustment to any violations was performed using the Greenhouse-Geisser correction.

5.4 Part 1: Results

The collective pre-intervention arm-swing values in the sagittal plane (shoulder flexion) for both the experimental and control groups are shown in Tables 5.1 to 5.5. The arm-swing condition that had the greatest effect on peak shoulder ω was the amount of arm back-swing used (short, medium and large arm back-swing). Table 5.1 shows the large arm back-swing condition being significantly higher than the medium arm back-swing condition in all trials (67° 90° large and 67° 90° medium, t (19) = 6.8, p = 0.001; 84° 90° large and 84° 90°

medium, t (19) = 3.3, p = 0.004; 84 45 large and 84° 45° medium, t (19) = 5.5, p = 0.001; 67° 45° large and 67° 45° medium, t (19) = 9.5, p = 0.001).

Table 5.1 Peak ω differences between large and medium arm back-swings in the sagittal plane (shoulder flexion).

	Group		
	Large back-swing	**Medium back-swing**	
Variable	Pre-test Peak ω (deg·s^{-1})	Variable	Pre-test Peak ω (deg·s^{-1})
67 90 Large	622 *	67 90 Medium	533.5
84 90 Large	606 *	84 90 Medium	510
84 45 Large	598.4 *	84 45 Medium	518.1
67 45 Large	597.8 *	67 45 Medium	510.8

***** Significant differences between arm-swing trials ($p < 0.05$).

Furthermore, within the two highest large back-swing trials (67° 90° large and 84° 90° large), participants utilised the larger of the two arm-swing starting positions (90°), suggesting that an increased countermovement in the arm-swing (overall from start (90°) to end of back-swing (large) yields the greatest increase in arm-swing velocity. Additionally, the participants' own choice of arm-swing also utilised a large back-swing (see Appendix 5.41) ranking higher than the medium arm back-swing trials (633.3 and 615.3 deg·s^{-1}).

The use of a medium back-swing over a short back-swing as seen in Table 5.2, demonstrated only one significant difference, with the medium backswing being significantly higher than the comparative short back-swing in the 84° 45° medium condition (t (19) = 3.4, p = 0.003).

Table 5.2 Peak ω differences between medium and short arm back-swings in the sagittal plane (shoulder flexion).

Group			
	Medium back-swing	**Short back-swing**	
Variable	Pre-test Peak ω (deg·s^{-1})	Variable	Pre-test Peak ω (deg·s^{-1})
67 90 Medium	533.5	67 90 Short	519.9
84 90 Medium	510	84 90 Short	512
84 45 Medium	518.1 *	84 45 Short	479.7
67 45 Medium	510.8	67 45 Short	497.1

***** Significant differences between arm-swing trials ($p < 0.05$).

Comparative values for all arm-swings performed from a starting position of 45° and 90° are shown in Table 5.3, demonstrating only one significant difference between the 84° 45° short and 84° 90° short conditions (t (19) = 4.1, p = 0.001). Irrespective of arm-swing start position (45° or 90°), the largest values observed in both conditions were the arm-swings performed with a large back-swing.

Table 5.3 Peak ω differences between a 45 and 90° arm-swing start position in the sagittal plane (shoulder flexion).

	Group		
	45 degree start	**90 degree start**	
Variable	Pre-test Peak ω (deg·s^{-1})	Variable	Pre-test Peak ω (deg·s^{-1})
84 45 Large	598.4	84 90 Large	606
84 45 Medium	518.1	84 90 Medium	510
84 45 Short	479.7	84 90 Short	512 *
67 45 Large	597.8	67 90 Large	622
67 45 Medium	510.8	67 90 Medium	533.5
67 45 Short	497.1	67 90 Short	519.9

***** Significant differences between arm-swing trials ($p < 0.05$).

In contrast, Table 5.4 showed no significant differences for the 84° and 67° seat trunk positions, indicating that the amount of arm back-swing utilised during arm-swings (large, medium and short) was the most important contributing factor for increasing peak shoulder ω.

Table 5.4 Peak ω differences between 67 and 84° trunk positions in the sagittal plane (shoulder flexion).

	Group		
	67 degree trunk flexion	**84 degree trunk flexion**	
Variable	Pre-test Peak ω (deg·s^{-1})	Variable	Pre-test Peak ω (deg·s^{-1})
67 90 Large	622	84 90 Large	606
67 90 Medium	533.5	84 90 Medium	510
67 90 Short	519.9	84 90 Short	512
67 45 Large	597.8	84 45 Large	598.4
67 45 Medium	510.8	84 45 Medium	518.1
67 45 Short	497.1	84 45 Short	479.7

***** Significant differences between arm-swing trials ($p < 0.05$).

Comparative values are shown in Table 5.5 for the concentric only arm-swings and all other conditions.

Table 5.5 Peak ω differences for concentric only arm-swings and the 45 and 90° start position arm-swings in the sagittal plane (shoulder flexion).

	Group		
	Concentric only arm-swing	**45 and 90° arm-swing**	
Variable	Pre-test Peak ω (deg·s^{-1})	Variable	Pre-test Peak ω (deg·s^{-1})
67 Concentric	597.8	67 45 Large	597.8
67 Concentric	597.8 *	67 45 Medium	510.8
67 Concentric	597.8 *	67 45 Short	497.1
67 Concentric	597.8	67 90 Large	622
67 Concentric	597.8 *	67 90 Medium	533.5
67 Concentric	597.8 *	67 90 Short	519.9
84 Concentric	593.4	84 45 Large	598.4
84 Concentric	593.4 *	84 45 Medium	518.1
84 Concentric	593.4 *	84 45 Short	479.7
84 Concentric	593.4	84 90 Large	606
84 Concentric	593.4 *	84 90 Medium	510
84 Concentric	593.4 *	84 90 Short	512

***** Significant differences between arm-swing trials ($p < 0.05$).

Interestingly, no significant differences were evident between the large and concentric-only back-swings, indicating that during the pre-test arm-swing measurements, the amount of swing available during the concentric part of the arm-swing appears to be the most important contributing factor to arm-swing velocity.

The collective pre-intervention arm-swing values in the frontal plane (shoulder flexion) for both the experimental and control groups are shown in Tables 5.6 to 5.10. Though less pronounced than the rank for the collective sagittal arm-swing values, the collective frontal arm-swing values demonstrate a similar trend, with ω for the large arm back-swing condition being significantly higher than three out of the four medium backswing conditions (67 45 medium and 67 45 large, t (19) = -4.4, p = 0.001; 67 90 medium and 67 90 large, t (19) = -3.7, p = 0.001; 84 90 medium and 84 90 large, t (19) = -4.1, p = 0.001).

Table 5.6 Peak ω differences between large and medium arm back-swings in the frontal plane (shoulder adduction).

Group			
	Large back-swing	**Medium back-swing**	
Variable	Pre-test Peak ω (deg·s^{-1})	Variable	Pre-test Peak ω (deg·s^{-1})
67 90 Large	491.2 *	67 90 Medium	444.9
84 90 Large	472.3 *	84 90 Medium	426.5
84 45 Large	416.3	84 45 Medium	403.6
67 45 Large	468 *	67 45 Medium	402.8

***** Significant differences between arm-swing trials ($p < 0.05$).

A comparison between the medium and short arm back-swing conditions is shown in Table 5.7, demonstrating one of the medium back-swings as also significantly higher than its comparative short back-swing (84 45 short and 84 45 medium, t (19) = -2.8, p = 0.011).

Table 5.7 Peak ω differences between medium and short arm back-swings in the frontal plane (shoulder adduction).

Group			
	Medium back-swing	**Short back-swing**	
Variable	Pre-test Peak ω (deg·s^{-1})	Variable	Pre-test Peak ω (deg·s^{-1})
67 90 Medium	444.9	67 90 Short	434.4
84 90 Medium	426.5	84 90 Short	408.2
84 45 Medium	403.6 *	84 45 Short	376.9
67 45 Medium	402.8	67 45 Short	402.9

***** Significant differences between arm-swing trials ($p < 0.05$).

Similar to the sagittal large back-swing values, the two greatest values were achieved using the largest starting arm position (90°), shown in Table 5.8. However, in contrast to the sagittal values, the comparative frontal values between the 45 and 90° start positions were significantly higher for the 90° start position in five of the six arm-swing conditions (67 45 short and 67 90 short, t (19) = -3.8, p = 0.001; 67 45 medium and 67 90 medium, t (19) = -3, p = 0.019; 84 45 short and 84 90 short, t (19) = -3.1, p = 0.005; 84 45 medium and 84 90 medium, t (19) = -2.3, p = 0.036; 84 45 large and 84 90 large, t (19) = -4.2, p = 0.001), indicating that an greater amount of swing during the early arm-swing is important for increasing arm-swing velocity in the frontal plane.

Table 5.8 Peak ω differences between a 45 and 90° arm-swing start position in the frontal plane (shoulder adduction).

	Group		
	45 degree start	**90 degree start**	
Variable	Pre-test Peak ω (deg·s^{-1})	Variable	Pre-test Peak ω (deg·s^{-1})
84 45 Large	416.3	84 90 Large	472.3 *
84 45 Medium	403.6	84 90 Medium	426.5 *
84 45 Short	376.9	84 90 Short	408.2 *
67 45 Large	468	67 90 Large	491.2
67 45 Medium	402.8	67 90 Medium	444.9 *
67 45 Short	402.9	67 90 Short	434.4 *

***** Significant differences between arm-swing trials ($p < 0.05$).

Comparative values for frontal arm-swings performed in the 67 and 84° seat position are shown in Table 5.9. They revealed that during one of the arm-swing conditions, peak arm-swing velocity was increased when sitting in the 67° seat position (67 45 large and 84 45 large, t (19) = 3.3, p = 0.004; 67 indicating that an increase in the angle of the trunk position is similar between sagittal and frontal plane arm-swing values.

Table 5.9 Peak ω differences between 67 and 84° trunk positions in the frontal plane (shoulder adduction).

Group			
	67 degree trunk flexion	**84 degree trunk flexion**	
Variable	Pre-test Peak ω (deg·s^{-1})	Variable	Pre-test Peak ω (deg·s^{-1})
67 90 Large	491.2	84 90 Large	472.3
67 90 Medium	444.9	84 90 Medium	426.5
67 90 Short	434.4	84 90 Short	408.2
67 45 Large	468 *	84 45 Large	416.3
67 45 Medium	402.8	84 45 Medium	403.6
67 45 Short	402.9	84 45 Short	376.9

***** Significant differences between arm-swing trials ($p < 0.05$).

Comparative findings for the frontal concentric only arm-swings are shown in Table 5.10. Five of the shorter (short and medium) back-swing conditions showed no significant increases during the concentric only arm-swings, and two of the large back-swing conditions were significantly less for the concentric only arm-swings (67 90 large and 67 concentric, t (19) = 3, p = 0.020; 84 90 large and 84 concentric, t (19) = 4, p = 0.001).

Table 5.10 Peak ω differences for concentric only arm-swings and the 45 and 90° start position arm-swings in the frontal plane (shoulder adduction).

	Group		
	Concentric only arm-swing	**45 and 90° arm-swing**	
Variable	Pre-test Peak ω (deg·s^{-1})	Variable	Pre-test Peak ω (deg·s^{-1})
67 Concentric	448	67 45 Large	468
67 Concentric	448	67 45 Medium	402.8
67 Concentric	448	67 45 Short	402.9
67 Concentric	448 *	67 90 Large	491.2
67 Concentric	448	67 90 Medium	444.9
67 Concentric	448	67 90 Short	434.4
84 Concentric	416.5	84 45 Large	416.3
84 Concentric	416.5	84 45 Medium	403.6
84 Concentric	416.5 *	84 45 Short	376.9
84 Concentric	416.5 *	84 90 Large	472.3
84 Concentric	416.5	84 90 Medium	426.5
84 Concentric	416.5	84 90 Short	408.2

***** Significant differences between arm-swing trials ($p < 0.05$).

The comparative pre and post-test arm-swing values (sagittal plane) for both the experimental and control groups are reported in Table 5.11.

Table 5.11 Mean values (± SD) for pre and post-test peak arm-swing ω in the sagittal plane (shoulder flexion), for both the experimental and control groups.

	Group			
	Experimental		**Control**	
Variable	Pre-test	Post-test	Pre-test	Post-test
	Peak ω (deg·s^{-1})		Peak ω (deg·s^{-1})	
67 45 Short	-483.9 ± 99.1	-501.9 ± 134.5	-510.4 ± 120.4	-489.9 ± 130.4
67 45 Medium	-485.6 ± 104.2	-532.7 ± 96.3	-535.9 ± 109.8	-554.7 ± 136.7
67 45 Large	-571.1 ± 132.6	-627.7 ± 109.2	-624.5 ± 113.8	-627.7 ± 152.9
67 90 Short	-493.2 ± 101.6	-525.7 ± 111.1	-546.6 ± 138.1	-568.9 ± 140.0
67 90 Medium	-498.1 ± 130.0	-553.5 ± 114.3	-568.9 ± 140.0	-563.5 ± 149.4
67 90 Large	-584.8 ± 132.3	-612.9 ± 77.7	-659.3 ± 101.8	-635 ± 101.1
84 45 Short	-457.1 ± 76.6	-466.8 ± 108.3	-502.4 ± 110.6	-475.3 ± 125.5
84 45 Medium	-493 ± 84.9	-445.2 ± 189.2	-543.1 ± 127.3	-535.2 ± 113.0
84 45 Large	-562 .4 ± 93.3	-559.2 ± 92.5	-634.4 ± 106.6	-583.7 ± 137.0
84 90 Short	-496.6 ± 78.8	-497.5 ± 99.8	-528 ± 110.3	-511.5 ± 135.6
84 90 Medium	-512.9 ± 85.3	547.7 ± 112.9	-506.9 ± 221.4	-544.4 ± 122.1
84 90 Large	-575.9 ± 76.4	-619.0 ± 114.9	-635.9 ± 102.0	-587.4 ± 151.7
67 Concentric	-565.6 ± 75.1	-589.8 ± 76.7	-630 ± 55.3	-571 ± 140.8
67 Own choice	-616 ± 114.5	-632.2 ±97.9	-651 ± 120.9	-603.5 ± 137.6
84 Concentric	-571.5 ± 89	-562.1 ± 83.0	-615.3 ± 97	-565.5 ±113.4
84 Own choice	- 610.8 ± 97.2	-600.1 ± 101.1	-619.9 ± 101.2	-575.8 ± 154

Notably, the group x trials interactions were not significant for any of the arm-swing conditions between pre and post-intervention values. However, a trend for an increase in peak arm-swing ω was observed for the majority of experimental post-test results with only a slight decrease in four conditions. Conversely, a trend for the peak arm-swing ω values for the control group's post-test results was far less evident, with an equal variation in both an increase and decrease in peak shoulder ω. Similar findings were observed in the pre and post-test values for the frontal plane (see Table 5.12), as again the group x trials interactions were not significant for any of the arm-swing conditions between pre and post-intervention values.

Table 5.12 Mean values (± SD) for pre and post-test peak arm-swing ω in the frontal plane (shoulder adduction), for both the experimental and control groups.

	Group			
	Experimental		**Control**	
Variable	Pre-test	Post-test	Pre-test	Post-test
	Peak ω (deg·s^{-1})		Peak ω (deg·s^{-1})	
67 45 Short	393.3 ± 84.4	404.7 ± 73.3	412.5 ± 74.1	438.8 ± 106.1
67 45 Medium	393.7 ± 104.8	448.6 ± 78.4	411.9 ± 96.8	448.6 ± 78.7
67 45 Large	447.9 ± 121.6	526.8 ± 98.3	488.0 ± 90.9	512.6 ± 98.2
67 90 Short	431.7 ± 96	450.5 ± 94.5	437.1 ± 77.6	471.2 ± 82.6
67 90 Medium	432.7 ± 118.5	459.2 ± 87.3	457.1 ± 78.8	504.8 ± 76.9
67 90 Large	471.3 ± 120.7	533.9 ± 64.5	511.0 ± 131.1	538.9 ± 84.1
84 45 Short	361.5 ± 93.6	366.7 ± 58.1	392.2 ± 81.0	419.7 ± 71
84 45 Medium	391.7 ± 102.2	417.2 ± 61.6	415.3 ± 90	460 ± 88.9
84 45 Large	394.4 ± 125.2	452.7 ± 90	438.3 ± 136.8	463.8 ± 140.4
84 90 Short	408.2 ± 83.4	389.6 ± 78.9	408.3 ± 79.3	431.4 ± 97.9
84 90 Medium	422.7 ± 115.1	452.2 ± 79.8	430.2 ± 77.5	473.7 ± 83.9
84 90 Large	470.1 ± 109.7	493.1 ± 89.4	474.5 ± 94.2	519.5 ± 105.4
67 Concentric	424.4 ± 68.1	484.1 ± 93.9	470.9 ± 125.7	460 ± 99.9
67 Own choice	481.8 ± 143.1	501.2 ± 111.5	485.5 ± 117.3	465.2 ± 82
84 Concentric	401.2 ± 71.4	439.9 ± 69	431.8 ± 124	440.6 ± 100.6
84 Own choice	416.1 ± 113.8	457.0 ± 102.7	464.7 ± 119.5	448.9 ± 114.8

5.8 Part 1 Discussion

In one of the most comprehensive and detailed examinations of upper-extremity arm-swing mechanics during vertical jumping, the current study demonstrated that an upper-extremity plyometric programme can be used to improve upper-extremity kinematics. Furthermore, this is the first study to assess the optimal arm-swing countermovement conditions during the arm-swing used in vertical jumping, by comparing arm-swings of elite basketball players during various types of seat position (trunk inclination), arm-swing start position (eccentric load) and also the amount of arm-swing back-swing utilised (magnitude). Additionally, the study also examined the effect of SSC utilisation during the arm-swing countermovement, comparing arm-swings that were performed using a concentric only movement.

The current study has confirmed the *a priori* hypotheses regarding the relationship between different arm-swing countermovement positions and the subsequent increase in arm-swing kinematics. Interestingly, there were no significant pre-post differences observed during any of the experimental group's arm-swing performance trials, indicating that the positive effect that the upper-extremity plyometric programme had on shoulder kinematics during the vertical jump (see part 2) was somehow not utilised during the arm-swing performance trials. Again, this was an unexpected finding, and when considering the experimental group's post-test AROM had significantly increased, a similar finding in the larger AROM arm-swings (large AROM back-swing) was justified. However, this was not observed in either the experimental or control groups post-test measurements, and so the *a priori* hypothesis previously stating that shoulder kinematics will increase in the large AROM arm-swings is rejected. Nonetheless, the large AROM arm-swings were shown to be the optimal arm-swing condition for achieving peak shoulder ω, and a trend of utilising either an increase in AROM or increase in eccentric load for increasing peak shoulder ω during the performance arm-swing trials was observed. Therefore, the *a priori* hypothesis previously stating that an increase in either AROM or eccentric load during the arm-swing performance trials will result in an increase in upper-extremity kinematics is accepted.

The optimal arm-swing kinematics during the arm-swing performance trials

The large AROM arm-swings represented the optimal arm-swing condition for achieving peak shoulder ω, reflected by the large back-swing trials being significantly higher than the medium and short AROM back-swing trials in all conditions (see Tables 5.1and 5.2). This suggests the arm-swing countermovement during vertical jumping required high eccentric loading to achieve the largest possible increases in peak shoulder ω, evidenced by the increase in peak eccentric shoulder ω and shoulder AROM that were observed in the post-test jump measurements in the experimental group. Interestingly, the increase in shoulder AROM during the large (back-swing) arm-swings suggests eccentric loading was increased, which according to the work by Moran et al. (2007) would indicate greater utilisation of the SSC. The greater range of motion used during the large AROM arm-swings would have allowed the participants to increase muscle pre-stretch, which has been argued as a prerequisite for increasing the amount of elastic energy developed (Lees et al., 2004) as well as its effective storage and reutilisation (Lees et al., 2006). Earlier work by Bosco et al. (1981) suggested the contractile components during increased muscle pre-stretch utilised greater cross bridge attachment, as the myosin heads were forcefully rotated further backwards during increased eccentric loads developing a greater ‘pull mechanism’ within the contractile components. Later work by Moran et al. (2007) argued this would only be true during the cross-bridge cycle time, and eccentric loads that were too great would have a negative impact on the muscle contractile components. Conversely, the findings in the present study show that the highest eccentric load during the arm-swing performance trials produced the greatest increase in concentric performance.

Research examining the production of elastic energy during high eccentric loads also suggests that a subsequent increase in concentric performance will follow (Lees et al., 2004). Furthermore, within the two highest score large back-swing trials (67 90 large and 84 90 large), both utilised the larger of the two arm-swing starting positions (90°), suggesting that a further increase of eccentric load during the arm-swing overall from start (90°) to end of back-swing (large) yields the greatest increase in arm-swing velocity. This is in contrast to the findings by Moran et al. (2007), who showed the highest eccentric loads during lower-extremity counter-movements having a negative impact upon concentric performance. This suggests there is an optimal eccentric load during counter-movements, and once this load is reached, an additional increase in load results in a decrease in performance. This could be an example of a balance between achieving the required muscle pre-stretch to facilitate utilisation of the SSC, elastic energy development, muscle active state and stretch reflex system (Bobbert et al., 2005; McBride et al., 2008; Gerodimos et al., 2008; Hara et al., 2008). The work by Moran et al. (2007) showed that as the magnitude (drop jump for 30 cm, DJ-30) and rate (90° AROM) of the countermovement utilised during vertical jumping increased, the subsequent concentric movement improved. However, the greater AROM condition (90° AROM) performed less well than an increased countermovement magnitude (DJ-30) coupled with a smaller AROM condition (70°), suggesting the increased eccentric load in the first condition had evoked a negative response to increased eccentric loading. This supports the research findings of Komi et al. (1997) who indicated that eccentric loads that are too high will increase GTO activation, inducing muscle relaxation and negatively impacting upon concentric performance. However, this was not shown in the current study’s findings, as the largest eccentric load arm-swings (90°) coupled with the largest AROM (large back-swing) produced the largest gains in peak shoulder ω. This may partly be due to the of load used during lower-extremity loading being representative of the whole body mass, as participants have to counteract the full weight of their body mass acting upon the lower-extremities. This is a factor that would not affect the eccentric load of the arm-swing during vertical jumping, as the participants in the current study only had to counteract their arm-segment mass, which possibly would not cause any GTO activation, and therefore not lead to a negative impact upon the subsequent concentric performance.

The largest peak concentric shoulder ω observed during the large backswing coupled with an increase in eccentric load (90° start position) suggests an increase in eccentric peak shoulder ω is best for producing the best arm-swing kinematics. The same finding was observed during vertical jump arm-swing data, as the post-test shoulder kinematic values demonstrate an increase in eccentric peak shoulder ω (111.2 $deg \cdot s^{-1}$) yielding a significant increase in sagittal peak shoulder ω (167.1 $deg \cdot s^{-1}$). Furthermore, the results from the performance arm-swing trials indicate that as eccentric load decreases (70°) coupled with a decrease in arm-swing AROM (short and medium back-swing), the resulting subsequent peak concentric shoulder ω also decreases (Figure 5.7). This is highlighted by the smallest values in peak concentric shoulder ω (479.7 and 497.1 $deg \cdot s^{-1}$) being observed during the smallest eccentric load condition coupled with the smallest arm-swing AROM condition (84 45 short and 67 45 short, respectively). Thus, it seems that low level eccentric loading during the arm-swing countermovement does not utilise the SSC as well as in the large eccentric load arm-swing trials, and a subsequent decrease in muscle pre-stretch, elastic energy development, stretch reflex facilitation and a lower muscle active state would all cause a decrease in concentric performance, as observed in the low level eccentric load arm-swings (Komi et al., 1997; Lees et al., 2004; Bobbert et al., 2005; McBride et al., 2008; Gerodimos et al., 2008; Hara et al., 2008).

The high level of eccentric load required to achieve the greatest gain in peak concentric shoulder ω could help explain why the participants' own choices of arm-swing was to use either a large back-swing (85%) or large starting position (80%) during their pre-test arm-swing trials. This could be indicative of elite basketball players' usual jump technique, as Chapter 4 in this thesis showed an increase in arm-swing AROM during vertical jumping was correlated with an increase in jump height for a sample of elite basketball players. However, a closer examination of the concentric only arm-swing performance trials demonstrates an unexpected finding in the current study. A comparison of the values between the concentric only arm-swings and all other conditions revealed that arm-swings performed with a short or medium back-swing were significantly less in peak shoulder ω than the concentric only arm-swings. Seemingly, elite basketball players prefer to use a maximum AROM (concentric only) arm-swing movement with no preceding countermovement than an arm-swing that only has small eccentric load or small arm-swing AROM. This is in contrast to the suggestion that an increase in eccentric loading results in an increase in concentric performance (Moran et al., 2007). Indeed, it seems that the arm-swing countermovement does require an increased level of eccentric load to increase peak concentric shoulder ω, as long as the eccentric load is large enough. Examination of the pre and post-test arm-swing data for the concentric only arm-swings suggests that the significant increase in peak shoulder ω when compared to the short and medium arm-swing conditions after completion of an upper-extremity plyometric programme was not apparent any more. This indicates that the increase in peak shoulder ω during the concentric only arm-swings, was only observed due to the participants' inability to utilise enough contribution from the SSC, and after completion of the plyometric training this had improved, therefore a significant difference was not observed in the post-test data. This is further evidence of the upper-extremity plyometric programme having a positive effect upon arm-swing kinematics, and the case for the training of the arm-swing during vertical jumping is strengthened.

The frontal arm-swing values demonstrate a similar trend to the sagittal arm-swings, with the large AROM arm-swings increasing peak shoulder ω significantly higher in three out of the four medium AROM arm-swings, and the two greatest values were achieved using the largest starting arm position (90°). Even though the frontal arm-swing trends are similar to those reported for the sagittal plane, the absolute values for peak frontal arm-swing movement were surprisingly high considering that previous investigators have referred to countermovement vertical jumping as a single-planar movement (Lees et al., 2004; Feltner et al., 2004; Hara et al., 2006; Hara et al., 2008). Although the mean peak value for each frontal plane movement was less than the mean peak value for each sagittal plane movement (suggesting that shoulder flexion is used more than shoulder adduction during arm-swings), the values were still high enough to indicate that the arm-swing is a multi-planar movement. However, the way in which the two different planes of motion contribute to vertical jump performance is probably quite different. That is, the sagittal plane arm-swing motion will directly increase the vertical displacement of the participant in the vertical direction (also in the sagittal plane), whereas the frontal plane motion may contribute more to the realignment of the arm-swing back at the midline of the body following anatomical adaptation during shoulder hyper-extension. This indicates that the frontal plane movement should be trained using the same techniques as used in the sagittal plane, and movement-specific exercises will train both planes of motion at the same time. This is further rationale for the development of movement-specific upper-extremity plyometric exercises that can improve the SSC utilisation during vertical jump performance. This would be an area for further investigation in subsequent studies.

Pre and post-test arm-swing kinematics during arm-swing performance trials

The main finding from the pre and post-test arm-swing performance trials for both the experimental and control groups was that there were no significant differences for any condition. Notably, no significant pre-post differences were found in the large AROM arm-swing conditions, which was an unexpected finding. Following a four-week upper extremity plyometric programme, it was hypothesised that the large AROM arm-swings would increase peak shoulder ω, as training the participants' ability to utilise the SSC should have resulted in an increase in the large AROM values, especially as this was the condition that would utilise the highest level of eccentric loading. Interestingly, the participants in the experimental group significantly increased their overall shoulder AROM in the post-test measurements (Table 5.1), indicating that the mechanics of their post-test large AROM arm-swings would also have been changed. Nonetheless, the data suggest that a trend for an increase in peak arm-swing ω was observed for the majority of the experimental group's conditions, with only a slight decrease in four conditions. Conversely, a trend for the peak arm-swing ω values for the control group's post-test results was not evident, with an equal variation in both an increase and decrease in peak shoulder ω.

A possible suggestion for the lack of significant changes observed may be that a learning affect occurred. The type of arm-swing movement used in performance arm-swing trials is the same as that used by athletes in vertical jumping, however, the chair used to analyse the arm-swing created arm-swing conditions that were considered not normal to the participants. Even though a habituation session was used in an attempt to increase the participants' exposure to the chair and the arm-swing protocol, a learning effect might still have occurred. Furthermore, securing segments that are normally moving during a vertical jump (such as the trunk) by means of the modified chair, suggests that the kinematic chain that is normally observed during vertical jumping would have been altered; such a change could explain why the arm-swing kinematics during the vertical jump trials significantly increased, whereas the arm-swing kinematics in the seated arm-swing performance trials did not. This is a limitation to the current study, and demonstrates the complexity of attempting to analyse a single moving segment that is part of a kinematic chain.

Future studies should consider analysing the optimal arm-swing conditions during the vertical jump. This option had been considered for the current study, however, changing the arm-swing conditions during vertical jumping would also affect the kinematics of the other joints that are moving at the same time, so any differences observed using this method would be hard to isolate. Nonetheless, the use of a secured chair for the purpose of solely analysing the arm-swing during vertical jumping indirectly isolated one of the main adjacent body segments (trunk) that has previously been shown to change position in response to arm-swing velocity. That is, the previous research by Vanrenterghem et al. (2008) suggested that an increase in arm-swing velocity caused an increase in trunk flexion (increased trunk inclination), which has also been shown to affect lower-extremity countermovement loading and the change in position of the body's COM (Hara et al., 2006). Therefore, performing arm-swing movements that are supposed to replicate the arm-swing during vertical jumping, but are performed whilst other key jump kinematics are restricted, implies findings from this part of the study cannot be directly applied to the performance of the arm-swing during vertical jumping. Moreover, this might explain why a significant pre-post difference in arm-swing kinematics was not shown, as the positive effect from the plyometric programme may only be seen in the arm-swing during normal vertical jump conditions and not whilst participants' were secured in a chair.

Another limitation to the current study is that the frontal plane movement had not been considered prior to the start of the pre-test measurements. This may have had an effect upon the design of the protocol, as participants were instructed during all sessions to attempt to swing their arms in the same forward motion every time, so sagittal plane movement would remain constant on each test day. However, the same consideration was not used for the frontal plane movements, mainly due to previous research indicating that the arm-swing during vertical jumping is a single planar movement (Lees et al., 2004; Feltner et al., 2004; Hara et al., 2006). Therefore, the participants could have used a different amount of frontal plane movement during the pre and post-test arm-swing conditions. However, the most important consideration for this study was the assessment of the sagittal plane arm-swing, as this directly contributes to the vertical movement of the participants' during vertical jump performance. Nonetheless, both the sagittal and frontal arm-swing movements appear to work together during vertical jumping and upper-extremity plyometric exercises need to accommodate this multi-planar movement. Furthermore, the arm-swing during vertical jumping also required further investigation, especially in response to an upper-extremity plyometric training programme. Therefore, part 2 in this study aimed to examine the use of an upper-extremity plyometric intervention for improving both arm-swing kinematics, and overall vertical jump performance.

5.5 Part 2: Introduction

Many athletes, coaches and sport scientists have advocated the use of plyometric exercises within training regimes, primarily for their ability to improve sports performance whilst increasing overall muscle power (speed and strength) (Chu, 1983; Chu et al., 1984; Holcomb et al., 1996a). Plyometric exercise is a specific type of exercise that is utilised by athletes to improve their ability to use the stretch shortening cycle (SSC), primarily by increasing muscle pre-stretch developed during a countermovement (Luebbers et al., 2003; Marinho et al., 2010) and facilitating a greater force produced in the muscle whilst shortening (Toumi et al., 2004; Lephart et al., 2005). The development of a rapid muscle pre-stretch during the eccentric phase of a countermovement has been depicted as a vital prerequisite for plyometric training (Chu et al., 1984; Moran et al., 2007; Villarreal et al., 2009a; Villarreal et al., 2009b), as demonstrated by high intensity exercises such as the depth jump (increased jump drop height, see figure 5.8), double squat hop and ballistic lunge (Chu, 1998).

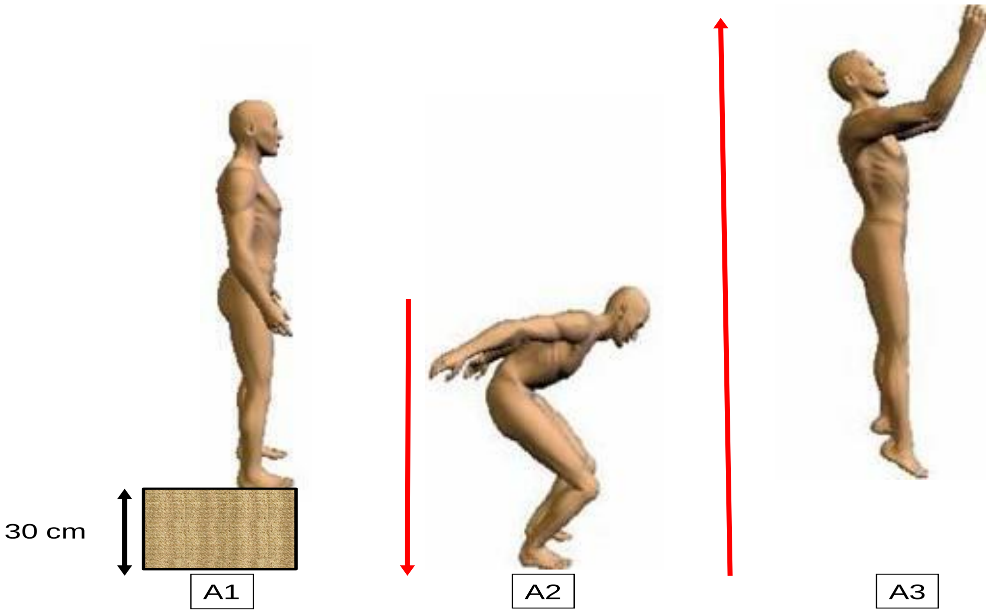


Figure 5.8 The depth jump from an increased drop jump height (30 cm) showing an increased eccentric load during the countermovement (A1 to A2), and subsequent increase in jump height (A2 to A3).

Plyometric exercises rely on a *high-intensity* principle, which according to Chu (1984) suggests that to gain maximal increases in jump height each exercise must be performed with maximal effort. This would suggest that plyometric programmes that consist of both high volume and high frequency plyometric exercises are difficult to maintain, which could result in athletes pacing themselves throughout the exercises, and therefore not achieving the required level of intensity. This agrees with the later work by Chu et al. (1998) that four variables (intensity, frequency, volume and recovery) must be considered when developing both plyometric-type exercises, and the actual programme itself. The optimal intensity, frequency and volume for plyometric programmes have been well considered in the literature (Fatouros et al., 2000; Turner et al., 2003; Villarreal et al., 2009a; Villarreal et al., 2009b; King et al., 2010), and established that typical increases in jump height range from 2 to 6 cm, typical frequencies are 4 to 12 weeks, and typical volume of exercises are 50 to 150 exercises performed 2 to 3 times a week. However, research conducted by Diallo et al. (2001) demonstrated an increase in jump height of only 3.4 cm after a 10-week plyometric programme comprised 250 repetitions each session, three times a week, suggesting a high frequency and volume do not directly lead to further increases in jump height. Furthermore, Maffiuletti et al. (2002) reported an increase of 5.2 cm upon completion of a programme comprised of less jumps over a shorter time period, and a reduced frequency and volume of training would be advantageous for completing each exercise with maximal effort.

Plyometric exercises have been successfully used to enhance aspects of performance in a wide variety of sports, such as tennis (Salonikidis et al., 2008; Suthakar et al., 2009), baseball (Ellenbecker et al., 2002) and football (Marques et al., 2010). However, they are most commonly used to help improve vertical jump ability (Villarreal et al., 2009a; Villarreal et al., 2009b; King et al., 2010). Notably, the increases in vertical jump height achieved whilst using plyometric exercises are currently exclusive to lower-extremity plyometric programmes

(Fatouros et al., 2000; Impellizzeri et al., 2008; Marques et al., 2008; Arabatzi et al., 2010; Khlifa et al., 2010; King & Cipriani, 2010), yet their use for training the upper-extremities is unexplored. Interestingly, the use of an arm-swing during vertical jumping is of equal importance to the lower-extremity countermovement in improving jump height (Feltner et al., 2004; Hara et al., 2006; Lees et al., 2004), demonstrated by an average increase in vertical jump height of 21.1 % when comparing jumps with and without an arm-swing. Furthermore, Feltner et al. (1999) argued that the arm-swing during vertical jumping added 9.3 % to VGRF, and reinforced its role in achieving jump height during vertical jumping. The findings by Feltner et al. (1999) were confirmed by those described in Chapter 3.4 and 3.5 in this thesis, in which a positive linear relationship between shoulder ω and jump height were observed. Furthermore, the ability to utilise an increase in the shoulders' AROM (increased countermovement) acted as a significant contributor to both peak arm-swing velocity and the subsequent increase in jump height. Importantly, the arm-swing is rarely considered as a key element of vertical jump training, which should be criticised as any increase in arm-swing velocity is likely to lead to an increase in jump height. However, no studies to date have examined the use of upper-extremity plyometric exercises as an intervention to increase vertical jump ability, and this warrants further investigation.

Most upper-extremity plyometric programmes are currently only prescribed for use in post-injury and post-surgery rehabilitation (Chmielewski et al., 2006), and rarely advocated for improving sports performance. Yet, research examining lower-extremity plyometrics has clearly demonstrated athletes increasing their vertical jump height in response to a wide variety of plyometric programmes (Innocenti et al., 2006; Moore et al., 2007; Markovic, 2007). This notwithstanding, a few studies have attempted to adapt upper-extremity rehabilitation exercises to be sport-specific, especially within baseball pitching (Swanik et al., 2002; Carter et al., 2007) where increases in throwing velocity (0.89 $m.s^{-1}$) were observed after four weeks of upper-extremity plyometric training (Carter et al., 2007). Furthermore, the exercises utilised within the programme were tailored to be movement-specific; that is, developed to produce a movement as close as possible to that used in baseball pitching. However, baseball pitching is a multi-planar movement that would have been difficult to replicate during plyometric exercise. Accordingly, those results could be misleading and possibly underestimate the increase that could be achieved in sports performance when using upper-extremity plyometric training (Swanik et al., 2002; Carter et al., 2007). Conversely, given that the arm-swing during vertical jumping is essentially a single planar movement (sagittal), movement-specific plyometric exercises would be far easier to both develop and use during training. Therefore, the principle aim of this study was to develop an upper-extremity plyometric programme that would utilise movement-specific exercises (arm-swing specific) aimed at increasing both arm-swing velocity and jump height. It was hypothesised that:

1. Jump height will increase in the experimental group after the four-week upper-extremity plyometric intervention.
2. Peak shoulder ω in the sagittal plane (shoulder flexion) will increase in the experimental group after the four week upper-extremity plyometric intervention.
3. Peak AROM for shoulder hyper-extension will increase in the experimental group after the four week upper-extremity plyometric intervention.

5.6 Part 2: Methods

Participants

These were the same as those described in Part 1 of this study.

Study design

The study involved an experimental design with repeated measures in which participants where evenly split and randomly assigned to either an experimental group (*n* = 10) or control group (*n* = 10). Both groups completed three countermovement vertical jumps using their normal technique, 72 hours after a habituation trial. Their jump height, jump phase time, upper and lower-extremity kinematics and each peak arm-swing velocity were subsequently used for data analysis. Upon completion of all the jump height measurements, the participants in the experimental group were required to complete a four week upper-extremity plyometric intervention, whilst the control group continued their normal sporting activities. The upper-extremity plyometric programme comprised of high volume (120 [week 1] – 540 [week 4] arm-swings) high intensity exercises (maximal effort), were performed for a short duration (4 weeks). Upon completion of the intervention, the baseline jump height measurements were performed by both groups for a second time; 72 hours post-intervention.

Pre-test procedures

Warm- up protocol

Each participant performed a standardised warm-up protocol comprising the same lower-extremity exercises used in Chapters 3 and 4 of this thesis.

Vertical jumps

Each participant was asked to step into the kinematic performance area (2 m x 2 m) with their arms at their sides and pause for 2 s. Each of the three CMJAs was performed with their own technique and maximal effort, with 60 s rest between individual jumps, and had to be completed in the performance area to minimise any horizontal displacement. Any jump landing outside the performance area was disregarded from the analyses and an extra jump was performed.

Three dimensional high-speed kinematic analyses

Arm-swing kinematics were captured using a 3D motion capture system, comprising 7 ProReflex MCU high speed cameras (Qualisys, 240 Hz, Sweden). Reflective spherical markers (15 mm; Qualysis, Sweden) were placed on sixty-five anatomical landmarks (n = 65 for calibration, n = 16 for anatomical, n = 49 for tracking) (Figure 5.9), on both sides of the body to define a twelve segment biomechanical model to be used for the jump trials (Lloyd, Alderson & Elliott, 2000; Wu et al., 2005; Roca et al. 2006; Roca et al., 2007; Chin et al., 2009). The performance area was calibrated prior to testing using a calibration frame and a calibration wand, after which a standing calibration of each participant with their arms in the anatomical position was conducted. Once the calibration was checked and deemed appropriate for model building, sixteen of the anatomical markers were removed in preparation for the jump trials.

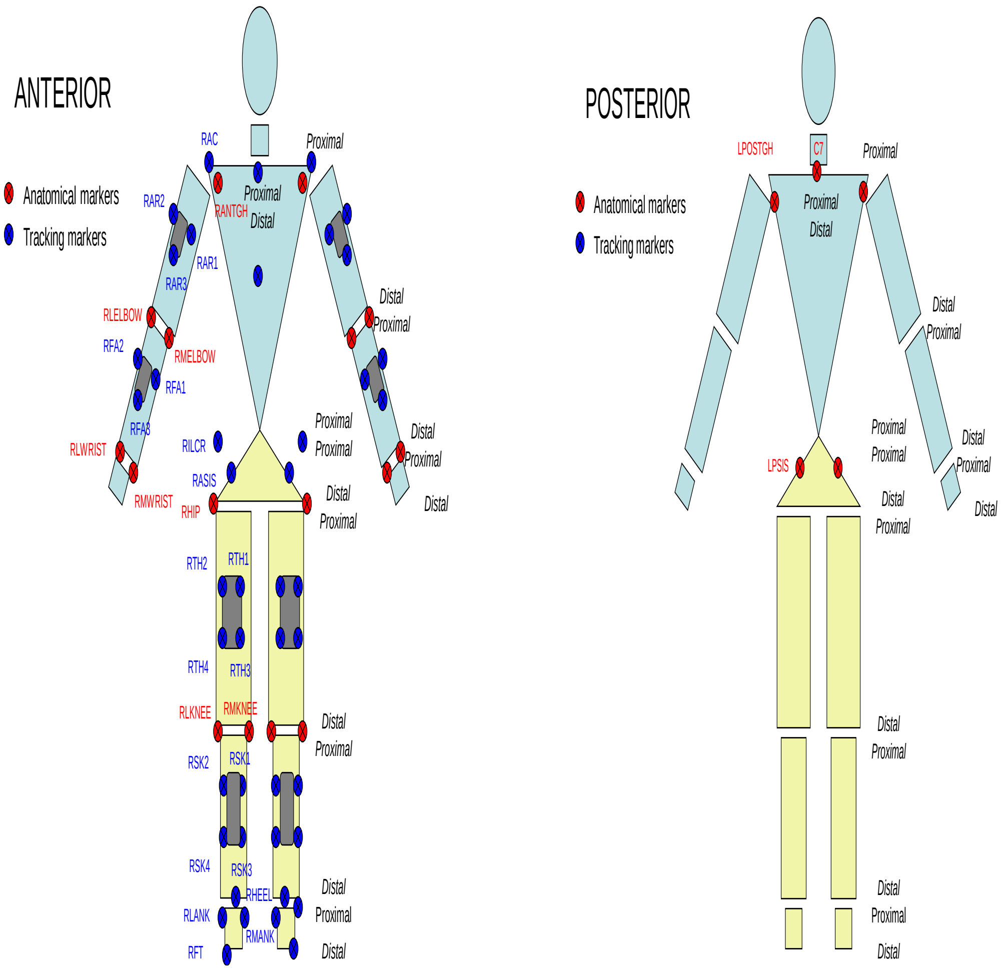


Figure 5.9 Twelve segment biomechanical model defined by sixty-five anatomical landmarks (adapted from Lloyd et al., 2004; Lees et al., 2004; Wu et al., 2005)

Biomechanical model

A full body multi-planar biomechanical model was developed from the University of Western Australia (UWA) full body marker set (Lloyd et al., 2000) combined with the CODA pelvis (Figure 5.10).

The gleno-humeral joint centre was defined using the UWA three marker shoulder triangulation system as previously mentioned in Part 1 in this study.

Upper-extremity plyometrics intervention

Participants took part in a four week upper-extremity plyometric intervention performing *high-intensity* plyometric exercises for one hour, twice a week (see Appendix 5.55 for full details regarding sets and repetitions). Eight upper-extremity plyometric exercises were adapted from previous ballistic medicine ball, theraband and light-weighted dumbbell exercises (Carter et al., 2007), and modified to become *movement-specific* to the arm-swing in vertical jumping. Each exercise was performed as hard as possible and constant positive verbal feedback was constantly given to participants' to ensure no pacing was occurring during the exercises.

The eight exercises are as follows:

1. Loaded single arm under-arm medicine ball rebound throws (short back-swing)

Facing a wall at a 1 m distance and standing in a semi-squat position with legs flexed at the knees (130 to 150°) and trunk inclined forwards with 70 to 90° of hip flexion, participants rebound a weighted jelly medicine ball (1 kg) against the wall (hip to shoulder height). The rebounding ball was caught in one arm in front of the body and the arm is brought backwards in movement that is representative of the back-swing phase of the arm-swing during CMJA. The participant was required to resist the eccentric load and use minimal back-swing (short back-swing) before the transition from the eccentric to concentric movement, and then rapidly throw the ball back at the wall. The exercise was repeated for the second arm.

2. Loaded single arm under-arm medicine ball rebound throws (max back-swing)

The exercise is identical to exercise one except for how far the medicine ball was drawn backwards during the arms back-swing. The participant was required to use a full back-swing, allowing almost full AROM of the shoulder to be utilised (large back-swing) before the transition from the eccentric to concentric movement, and then rapidly throwing the ball back at the wall. The exercise was repeated for the second arm.

3. Loaded single arm under-arm weighted arm-swing burnouts (dumbbell)

This exercise uses the same start position and full back-swing as exercise two. The single arm was swung as fast as possible during both eccentric and concentric movements whilst holding a single dumbbell (1 kg). The exercise was repeated for the second arm.

4. Loaded two arm medicine ball reverse overhead throws

Starting opposite a partner with a large medicine ball (3 kg) in a semi-squat position (knees flexed, 130 to 150°; hip flexed, 70 to 90°), the legs are in a wide stance and a small amount of hip abduction. The arms receive the ball along the floor between legs from a distance of 1 m with two hands before rapidly flexing again to move the ball into an overhead position and finally letting the ball release to be thrown over the head.

5. Loaded two arm medicine ball suicide drops

Starting in a kneeling position with the shoulders flexed maximally and holding a large medicine ball (3 kg), the arms extend at the shoulders allowing the ball to drop to the torso with two hands before rapidly flexing again to move the ball into an overhead position and finally stopping as fast as possible.

6. Loaded single arm under-arm medicine ball floor slams

Facing a partner at a 2 m distance and standing in a semi-squat position with legs flexed at the knees (130 to 150°) and trunk inclined forwards with 70 to 90° of hip flexion, the arm receives the ball along the floor to the side. The participant is required to resist the eccentric load using a full back-swing (large back-swing) before the transition from the eccentric to concentric movement, then the arm rapidly flexes at the shoulder before releasing the ball at the low-point of the arm down-swing and throwing the ball into the floor. The exercise was repeated for the second arm.

7. Eccentric loaded two arm theraband arm down-swings (high load position)

Facing away from a wall with a high bar at a 1 m distance away and a 3 m height, and kneeling down in a semi-squat position with legs flexed at the knees (130 to 150°) and trunk inclined forwards with 70 to 90° of hip flexion, participants hold a low resistance theraband (blue) with both arms fully hyper-extended at the shoulder. The theraband is used to resist shoulder flexion and assist in increasing the eccentric loading during the shoulder extension. The movement was performed as quickly as possible.

8. Eccentric loaded two arm theraband arm down-swings (low load position)

This exercise was the same as exercise seven except for using a low bar at a 1 m distance away and a 1 m height.

Each exercise was performed with maximal effort for each individual trial (high-intensity), and no pacing throughout the exercises was to be utilised. The medicine ball and dumbbell weight was maintained at a minimal weight (1kg) and was not increased throughout the intervention, allowing the exercise to remain at high-intensity whilst still being performed at maximum speed with minimum transition between the eccentric and concentric movements.

Data processing

Vertical jump height was measured by recording the vertical displacement of the right anterior superior iliac spine marker (RASIS), and was tracked from the point the toes leave the ground (take-off) until the point where the hip marker ceases vertical displacement (apex of the jump). The highest jump from each condition was used for analysis. The kinematic data for the CMJA trials were analysed using key movement events throughout the trials and collated at the starting position for each phase. The key arm-swing events that were recorded using visual 3D software were the start position, maximum shoulder hyper-extension (end of arm-swing countermovement), arm-swing low point (defined by the lateral wrist marker lowest point during the arm down-swing phase) and finally the arm-swing finish position (end position).

Statistical analyses

The variability of the sample's kinematic results were assessed using separate two-way (group and trials) analysis of variance with repeated measures (ANOVA). The assumption of sphericity for each test was analysed using the Mauchly test, and adjustment to any violations was performed using the Greenhouse-Geisser correction. Upon satisfaction that a significant group x trial interaction was observed, post-hoc analysis was performed using paired sample *t*-tests for the overall sample with the alpha level set at $P \leq 0.05$.

5.7 Part 2: Results

The descriptive statistics for AROM and CMJ during the pre and post-test conditions for both the experimental and control groups are reported in Table 5.13. Notably, for maximum displacement of the right ASIS marker, the group x trials interaction was significant (F=12.1, $P = 0.003$), with post-hoc analysis revealing a significant ($P < 0.05$) increase (7.2 cm) in the experimental group only. Similarly for AROM, a significant interaction affect (F=36.0, $P = 0.005$) was explained by a rise in the experimental group only (+ 5.3°) following the intervention. The low point of the ASIS marker shows the average depth of the squat during the vertical jump trials.

Table 5.13 Mean values (± SD) for pre and post-test peak kinematic variables and jump height (cm) for both the experimental and control groups.

	Group			
	Experimental		**Control**	
Variable	Pre-test	Post-test	Pre-test	Post-test
Max ASIS (mm)	1480.9 ± 64.7	1552.8 ± 95.8*	1522.2 ± 84.4	1520.3 ± 66
Low ASIS (mm)	697.2 ± 94	689.1 ± 102.3	675.8 ± 62.3	679.1 ± 67.7
Max jump (cm)	47 ± 5.8	54.2 ± 8.3*	52.3 ±6.1	52.1 ± 4.8
Arom (°)	63.3 ± 9.5	68.6 ± 8.4*	65.5 ± 11.8	65.4 ± 11.5

* Significant differences to pre-test values ($p < 0.05$).

Max ASIS: Mean (±SD) maximum displacement of the right ASIS marker (mm).

Low ASIS: Mean (±SD) minimum displacement of the right ASIS marker (mm).

Max jump: Mean (±SD) jump height (cm).

AROM: Mean (±SD) maximum shoulder hyper-extension AROM (°).

The key kinematic jump variables are presented in Table 5.14. Lower-extremity, elbow and full shoulder kinematics are reported in the sagittal, frontal and transverse planes. The group x trials interaction for peak sagittal shoulder ω was significant (F=10.5, $P = 0.004$), with post-hoc analysis revealing a significant ($P < 0.05$) increase (167.1 deg·s^{-1}) in the experimental group only. Similarly for peak shoulder ω in the frontal plane, a significant interaction affect (F=13.2, $P = 0.002$) was observed by an increase in the experimental group only (+121 deg·s^{-1}) following the intervention. The group x trials interaction revealed no significant difference for the ankle, knee, hip and elbow joints, as well as peak shoulder ω in the transverse plane.

Table 5.14 Mean values (± SD) for pre and post-test peak ω for both the experimental and control groups.

	Group			
	Experimental		**Control**	
Joint	Pre- test	Post-test	Pre-test	Post-test
	Peak joint ω (deg·s-^{1})		Peak joint ω (deg·s-^{1})	
Ankle	871.6 ± 89	858 ± 125.5	786.7 ± 244.7	809.2 ± 177.4
Knee	955.4 ± 89.1	967.5 ± 119.6	939.4 ± 122.2	896.1 ± 182.9
Hip	495.3 ± 102.1	496 ± 115.4	484.3 ± 116.1	463.9 ± 79.4
Shoulder				
Sagittal	622.8 ± 163.4	789.9 ± 96.9*	626.7 ± 128.6	599.3 ± 199.8
Frontal	431 ± 127.4	552 ± 116.4*	547.8 ± 170.6	473.1 ± 107.9
Transverse	386.7 ± 260.9	408.3 ± 201.9	491.3 ± 205.9	517.6 ± 130.8
Elbow	282.6 ± 104.8	311.3 ± 104.8	362.8 ± 171.4	344.3 ± 95.2

* Significant differences between jump types ($p < 0.05$).

5.8 Part 2 Discussion

In one of the most comprehensive and detailed examinations of upper-extremity plyometrics, and their use for increasing vertical jump performance to date, the current study demonstrated that an upper-extremity plyometric programme can improve both vertical jump height and the velocity and ROM of the arm-swing. Furthermore, this is the first study to assess the optimal arm-swing countermovement conditions during the arm-swing used in vertical jumping, by comparing arm-swings of elite basketball players during various types of seat position (trunk inclination), arm-swing start position (eccentric load) and also the amount of arm-swing back-swing utilised (magnitude). Additionally, the study also examined the effect of SSC utilisation during the arm-swing countermovement, comparing arm-swings that were performed using a concentric only movement.

The current study has confirmed the *a priori* hypotheses regarding the effect of arm-swing kinematics on vertical jump performance, especially in light of the increased post-intervention values for jump height (7.2 cm) and peak shoulder AROM (5.3 °) for the experimental group only. Moreover, the arm-swing kinematics (shoulder joint) for the plyometric group during the post-test vertical jump values showed a significant increase in the sagittal (+ 167.1 $deg{\cdot}s^{-1}$) and frontal (+ 121 $deg{\cdot}s^{-1}$) peak shoulder ω values. Similar to the control group, there were no significant differences observed in peak shoulder ω in the transverse plane of motion. However, the absolute values for peak shoulder ω in the transverse plane (386.7 ± 260.9, 408.3 ± 201.9, 491.3 ± 205.9 and 517.6 ± 130.8 $deg{\cdot}s^{-1}$) during the pre and post-test values for the experimental and control groups, respectively demonstrate the arm-swing during vertical jumping as a highly active multi-planar movement, which was an unexpected finding. This was due to the majority of the forward swinging movement of the arms occurring in the sagittal plane (shoulder flexion) (Lees et al., 2004). Importantly, the absolute value for peak shoulder ω in the sagittal plane occurs early during the arm down-swing movement, which is the same time when peak shoulder ω can be observed in the frontal plane (arm-swing adduction). This indicates that arm-swing adduction plays a vital role in the initial forward swinging movement of the arms, and should be considered in future upper-extremity plyometric programmes.

Interestingly, there were no significant pre-post differences observed during any of the experimental group's arm-swing performance trials. The upper-extremity plyometric programme did not significantly increase arm-swing velocity whilst the participant's were strapped into a secured chair, however, during the vertical jump trials, both arm-swing velocity and jump height significantly increased, indicating that the plyometric exercises had a positive effect on the jump kinematics as a whole and just an isolated improvement in the arm-swing. Again, this was an unexpected finding, and when considering the experimental group's post-test AROM had significantly increased, a similar finding in the larger AROM arm-swings (large back-swing) was justified. However, this was not observed in either the experimental or control groups post-test measurements, and so the *a priori* hypothesis previously stating that shoulder kinematics will increase in the large AROM arm-swings is rejected. Nonetheless, the large AROM arm-swings were shown to be the optimal arm-swing condition for achieving peak shoulder ω, and a trend of utilising either an increase in AROM or increase in eccentric load for increasing peak shoulder ω during the performance arm-swing trials was observed. Therefore, the *a priori* hypothesis previously stating that an increase in either AROM or eccentric load during the arm-swing performance trials will result in an increase in upper-extremity kinematics is accepted.

Vertical jump performance upon completion of an upper-extremity plyometric intervention

The pre-test jump height values observed in the current study are similar to previous findings for elite basketball players, with the experimental group's jump height of 47 ± 5.8 cm similar to that of 44.7 ± 6.5 cm observed in Chapter 4 of this thesis, as well as similar findings of 48.1 ± 3.6 cm in National League volleyball players (Bobbert et al., 1996). The larger jump height observed in the control group (52.3 cm) was primarily caused by high values of three of the randomly assigned participants, ranging between 58.7 and 60.9 cm, which were considerably higher than the greatest value observed in the experimental group (52.5 cm). However, the control group showed no significant change in jump height over the course of the study (- 0.2 cm), suggesting that the jump trials performed on both the pre-and post-test measurement days were standardised and well controlled. In contrast, the post-test vertical jump measurements for the upper-extremity plyometric training group had increased significantly (+ 7.2 cm), which when compared to previous studies that have examined lower-extremity plyometric programmes, indicates that upper-extremity plyometrics are more effective than the highest responding equivalent lower-extremity plyometrics, that yielded increases of 5.2 and 6 cm (Maffiuletti et al., 2002 and Fatouros et al., 2000, respectively). Moreover, other lower-extremity plyometric programmes have also demonstrated far smaller increases in peak vertical jump, ranging from the lowest gain of 2 cm (Turner et al., 2003), to 3.35 cm during a relatively low frequency programme (Clutch et al., 1983), and 4.8 cm during a programme that lasted twenty four weeks (Hakkinen et al., 1985).

Work by Villarreal et al. (2008) demonstrating an increase in jump height of 5.2 cm argued that the duration, frequency and volume of plyometrics utilised during previous lower-extremity programmes, would have directly affected the increase in vertical jump height. Chu et al. (1998) had suggested similar factors as responsible, that is intensity, frequency, volume and recovery. However, the optimal variation of these factors was not offered. Villarreal et al. (2008) indicated that if athletes have the ability to achieve better results in a smaller time period, this should be advocated. Later work by Villarreal et al. (2009b) used a comparative meta-analysis to highlight the sparse findings by previous investigators that examined lower-extremity plyometric programmes using various combinations of duration, frequency and volume. For example, an increase of 3.4 cm after a programme comprised 250 exercises, 3 times a week for 10 weeks (Diallo et al., 2001) is clearly not comparable to a study demonstrating an increase of 4 cm after a programme of 50 exercises performed 4 times a week for 3 weeks (Fowler et al., 1995). Collectively, the programme offered by Diallo et al.

(2001) required athletes to complete a total of 7500 repetitions of exercise compared to only 600 repetitions of exercise completed in the programme by Fowler et al. (1995). Therefore, the suggestion offered by Villareal et al. (2008) that a greater quantity of plyometric exercise does not equate into greater increase in vertical jump height seems justified. Further work by Villarreal et al. (2009b) highlighted intensity as a key factor that was not controlled well throughout previous lower-extremity plyometric programmes. This could help explain the large vertical jump gain observed in the current study, as each plyometric exercise performed during the upper-extremity plyometric programme was executed with maximal effort.

According to Chu (1998), plyometric exercises that are performed with sub-maximal effort can actually have a negative impact upon sporting performance. It could be suggested that plyometric programmes that comprise high frequency or high volume exercises, such as those highlighted previously, could cause athletes to exercise sub-maximally, as a high frequency and high volume of exercise would be difficult to perform each exercise with maximal effort. Moreover, when related to the mechanics of vertical jumping, athletes exercising sub-maximally during plyometric training would also have a direct impact upon several associated mechanisms that are linked to plyometrics and the SSC. Chu (1998) argued that maximal performance of each exercise would increase the rapid muscle pre-stretch during the eccentric phase of the countermovement during each exercise, and this would increase the utilisation of the SSC and enhance the force produced in the muscle whilst shortening (McBride et al., 2008). Furthermore, an increase in muscle pre-stretch during an eccentric muscle contraction has been linked to an increase in the effective storage and utilisation of elastic energy (Bobbert et al., 1996; McBride et al., 2008), as well as an increase in potentiation of the contractile components (Binder-McCleod et al., 2002) and an increase in the active state development in muscles (Bobbert et al., 1996; Bobbert et al., 2005), all of which have been shown to improve the subsequent performance of the following concentric contraction. This suggests that maximal effort plyometric exercise is vital for increasing the usage of the SSC mechanisms, whereas sub-maximal plyometric exercise would result in these mechanisms also working sub-maximally, leading to a decrease in performance. Moreover, this suggests that plyometric training with poor sub-maximal type exercises would also be a waste of both coach and athlete time.

Arm-swing kinematics during the pre and post-test vertical jumps

The plyometric programme utilised in the current study targeted the countermovement of the arm-swing, and aimed to improve the whole of the arm-swing during vertical jumping. Therefore, to develop a better understanding of how peak vertical jump height has increased on average by 7.2 cm by only training the upper-extremities, the following section will focus upon the arm-swing kinematics and their effect upon jump performance. A primary aim of this study was to assess the arm-swing contribution to vertical jumping and the arm-swings' suitability for plyometric training, and the post-test shoulder kinematic values for sagittal plane shoulder flexion demonstrate a significant increase in peak shoulder ω (+ 167.1 $\text{deg}\cdot\text{s}^{-1}$). This suggests that the increase in jump height (7.2 cm) for the experimental group during the post plyometric intervention measurements resulted directly from the increase in arm-swing velocity. Research examining the production of elastic energy during SSC type movements also suggests that an increase arm-swing velocity would effectively increase the production of elastic energy in the upper-extremities (Lees et al., 2004), which when reutilised in the latter phases of the jump, would have contributed to the increase in jump height.

In the current study, the increase in peak shoulder ω of the arm-swing indicates the arms working at a faster rate. Work by Vanrenterghem et al. (2008) indicated this could increase the speed and magnitude of trunk flexion and an increase in the speed of the arm-swing countermovement in the current study would support this suggestion. Therefore, using upper-extremity plyometrics to increase the arm-swing countermovement should be advocated for increasing jump height. Moreover, the increase in arm-swing velocity during the arm-swing countermovement suggests that upper-extremity plyometric training results in faster positioning of the trunk, which occurs from the increase in trunk flexion and changes in the position of the body's COM. By developing greater trunk flexion (trunk inclination), this would result in an increase in the proximal to distal loading of the upper-extremities kinematic chain. According to the work by Hara et al. (2006) this causes an increase in the lower-extremity loading (lower-extremity countermovement), as this is occurring simultaneously at the end of the arm-swing countermovement. Interestingly, this suggests a direct relationship between the increase in the arm-swing countermovement, and a subsequent increase in lower-extremity loading, which according to Moran et al. (2007), will effectively contribute to an increase in jump height. The speed of the kinematic chain that is initiated by the arm-swing countermovement, and all the proposed linked mechanisms that occur during the arm-swing countermovement, appears to improve directly as a result of an increase in arm-swing velocity. Furthermore, the arm-swing concentric movement and jump height had increased post-intervention, suggesting upper-extremity plyometrics had not only improved arm-swing velocity, but this had also had a positive effect on the rest of the jump mechanics.

When the two groups pre-test absolute peak shoulder ω values (sagittal plane) in the current study (-622.8 ± 163.4 and -626.7 ± 128.6 $deg{\cdot}s^{-1}$, experimental and control group, respectively) are compared to the arm-swing kinematic values that were analysed using two dimensional (2D) high-speed video analyses in Chapter 3 (748.3 ± 98.8 $deg{\cdot}s^{-1}$), they appear to underestimate those that are analysed in 2D. To explain this finding, it is important to understand the differences between single and multi-planar movements. The arm-swing during vertical jumping has previously been described essentially as a single planar movement (Less et al., 2004; Feltner et al., 2004), yet the 3D data in the current study has revealed a notable amount of frontal (431 ± 127.4 and 547.8 ± 170.6 $deg \cdot s^{-1}$) and transverse (386.7 ± 26.9 and 491.3 ± 205.9 $deg \cdot s^{-1}$) plane movement, which could explain why the 3D system data are lower than that produced using 2D analyses. That is, any movement occurring out of the sagittal plane would have not be picked up when using 2D analysis, therefore could have been lost, and the combined frontal and sagittal movements would have been reported as a single planar movement only (sagittal). However, both the frontal and transverse plane movements would have had less affect upon the overall vertical jump performance, as the vertical plane reflects movement in the sagittal plane. Notwithstanding this comment, the missing frontal data from the previous studies 2D analysis needs to be acknowledged as a possible limitation to the findings in Chapter 3.

The largest contributing plane of motion to arm-swing kinematics during vertical jumping still remains the sagittal plane (-789.9 ± 96.9 $deg \cdot s^{-1}$, post-training), and is the only movement in the current study to significantly increase over the course of the intervention (+ 167.1 $deg \cdot s^{-1}$). However, future studies should also include upper-extremity plyometric exercises that train the frontal aspect of the arm-swing movement during vertical jumping, as this could lead to even greater gain in arm-swing velocity and jump height. Interestingly, the movement of the arm-swing in the frontal plane appears to be due to abduction and adduction of the arms during the latter stages of shoulder hyper-extension, which at this point, the arms are pulled away from the body to allow the arm-swing to be drawn further backwards. At the end of the arm-swing countermovement (back-swing), adduction of the arms occur to bring the arm-swing back into line with the body, and the only muscle group to create this adduction movement is the large pectoralis major muscle group, suggesting that the arm-swing can utilise muscle contractions from both the shoulder (anterior deltoid) and chest (pectoralis major) muscle groups, inevitably leading to synchronised shoulder adduction and shoulder flexion during the early stages of the concentric performance of the arm-swing. However, muscle activity (via electromyography) has not been examined in the current study and would be a useful addition for future studies in this area of research.

The use of frontal plane shoulder adduction during the arm-swing in vertical jumping was an unexpected finding, and suggests that anatomically the arm-swing is attempting to reach as far backwards as possible during the arm-swing countermovement, as allowing the arms to adduct during the arm countermovement will effectively increase the participant's AROM during shoulder hyper-extension. Interestingly, during the post-test measurements for the experimental group, a significant increase in AROM for shoulder hyper-extension was observed (+ 5.3°), which suggests that upper-extremity plyometric training can increase shoulder flexibility, and this may be a further contributing factor to the observed increase in jump height. A previous study examining elite basketball players arm-swing mechanics during vertical jumping indicated that an increase in the amount of utilised AROM at the shoulder joint was significantly correlated with an increase in jump height (See Chapter 3.5 and 3.6 of this thesis), therefore, considering the upper-extremity plyometric group significantly increased their shoulder AROM after completion of the plyometric intervention, the use of upper-extremity plyometric exercises to increase arm-swing kinematics and the subsequent increase in jump height is once again advocated. Furthermore, it should be suggested that athletes train to increase both arm-swing velocity at the same time as improving their arm-swing flexibility, as to increase the availability of AROM at the shoulder will lead to further increases in arm-swing velocity.

Interestingly, the use of increased amounts of shoulder AROM suggests the concentric phase of the arm-swing would have more time to develop force, which according to Bobbert et al. (1996), is one of the primary ways in which the utilisation of a countermovement allows the subsequent concentric movement to be improved. An increase in the amount of AROM available during the arm-swing, as occurred in this study (+ 5.3°), would invariably increase the eccentric load (shoulder flexor muscles) and a subsequent increase in muscle pre-stretch. Work by Moran et al. (2007) who examined various eccentric loads in the *lower-extremity* countermovement, noted that an increase in lower-extremity eccentric loading yielded an increase in vertical jump height, and that the magnitude of eccentric load was proportional to the amount of AROM utilised. It follows, therefore, the increase of 7.2 cm found in this study was partly due to the amount of AROM utilised during the arm-swing countermovement. This presents further evidence for the positive effect that upper-extremity plyometric exercises can have on arm-swing mechanics during vertical jumping, and justifies their use for increasing jump height. The positive contributions to vertical jump performance shown previously in the lower-extremities (Moran et al., 2007) and currently in the upper-extremities, indicates that future studies should examine an overall combined plyometric training programme. That is, training the lower-extremity countermovement and arm-swing countermovement at the same time, primarily aimed in increasing overall vertical jump mechanics, and therefore this warrants further investigation.

5.5 Conclusion

The current two-part study has demonstrated that elite basketball players significantly increasing their jump height, peak shoulder ω, peak frontal shoulder ω and peak shoulder AROM after completing a four-week upper-extremity plyometric programme comprised of arm-swing specific exercises. Moreover it is suggested there is a kinematic link between the observed increase in peak arm-swing movement and the overall increase in jump height. The primary source for the increase in both jump height and arm-swing velocity can be attributed to the participants increased ability to use the SSC after plyometric training, resulting directly from an increase in muscle pre-stretch and the subsequent increase in elastic energy development, muscle active state and stretch reflex utilisation (Bobbert et al., 2005; McBride et al., 2008; Gerodimos et al., 2008; Hara et al., 2008). Overall, this indicates that an upper-extremity plyometric programme can yield an increase in arm-swing kinematics and a subsequent increase in jump performance. Therefore upper-extremity plyometric exercises should be advocated for athletes wishing to increase their jump height.

The arm-swing used during vertical jumping has previously been described essentially as a single planar movement (Lees et al., 2004; Feltner et al., 2004), however, the results in the current study indicate that the arm-swing is a complex multi-planar movement, and analysing the arm-swing should only be performed using 3D analysis. Furthermore, if upper-extremity plyometric exercises can increase arm-swing kinematics in the sagittal plane, the same principle could be applied for developing upper-extremity plyometrics that specifically target the frontal plane movement of the arm-swing.

CHAPTER 6

GENERAL CONCLUSIONS

6.1 Main findings

Study 1 revealed that the arm-swing during a countermovement jump (CMJ) is highly active prior to the propulsion of the legs, with peak ω at the shoulder (748.3 ± 98.8 $deg \cdot s^{-1}$) occurring prior to the start of the leg propulsive phase 100% of the time. Notably, the findings in study 1 demonstrated the arm-swing during vertical jumping initiating the start of the CMJ movement, justifying arm-swing mechanics requiring further exploration during the early jump phases (arm back-swing and down-swing). Study 1 also showed a positive linear relationship between peak arm-swing velocity and peak vertical jump height (r = 0.470), giving an early indication that if arm-swing velocity was to be trained to become faster, vertical jump height should increase. Interestingly, the participants' peak arm-swing velocity was shown to be dependent upon the participants' ability to utilise a large amount of their shoulders' maximum available AROM, indicating peak shoulder ω and peak utilisation of shoulder AROM are good contributing factors to jump height.

The ability to utilise a fast arm-swing in study one resulted in a higher achievement in jump height, and similar findings had previously indicated that an increase in arm-swing velocity could lead to an increase in the production and transfer of energy (Lees et al., 2006), lower-extremity eccentric loading (Moran et al., 2007) and a faster proximal to distal sequence of joint rotations (Hara et al., 2006). Moreover, the work by Lees et al. (2004) indicated that facilitation of the pre-mentioned mechanisms would require peak arm-swing velocity to occur early during the concentric part of the arm-swing, and as close to the transition from the eccentric movement as possible. This indicated that the preceding eccentric arm-swing phase (arm-swing countermovement) was an important consideration for overall arm-swing mechanics, and therefore the role of the arm-swing countermovement needed further exploration. Furthermore, previous research examining the contribution from a countermovement in the lower-extremities during vertical jumping, demonstrated an increase in utilisation of the stretch-shortening cycle (SSC) when compared to jumps performed with none (Bobbert et al., 2005), and this lead to an increase in both the concentric performance in the lower-extremities and overall jump height. Interestingly, the same SSC utilisation could be used during the arm-swing countermovement in vertical jumping, suggesting that the subsequent concentric arm-swing phase will also be improved.

The primary aim of Study 2 was to examine vertical jumps performed with and without an arm-swing countermovement, primarily aimed at identifying the contribution of the SSC. The main findings were that jumps performed with an arm-swing countermovement significantly increased mean jump height (+ 6.2 cm) and mean peak shoulder ω (+ 67.5 deg·s-1). The increase in mean peak shoulder ω in the arm-swing countermovement condition (+ 67.5 deg·s-1) indicates that arm-swing mechanics during the concentric phase of the arm-swing were improved as a direct result from utilising an eccentric phase countermovement. The main contributing factor to the increase in peak concentric arm-swing velocity was attributed to the participants' ability to utilise the SSC during the arm-swing countermovement, which would have led to an increase in the transfer of elastic energy, development of a higher muscle active state, greater facilitation of the stretch reflex system and an improved utilisation of the muscle contractile components (Komi et al., 1997; Bobbert et al., 2005; McBride et al., 2008; Gerodimos et al., 2008; Hara et al., 2008), as previously shown. Therefore, it was concluded that the arm-swing countermovement made a contribution to vertical jump performance.

Study 2 also revealed that the location of peak shoulder ω had a direct affect upon jump height, reflected by a significantly shorter time to peak velocity (- 0.036 s) when using an arm-swing countermovement, and peak shoulder ω occurring during the important down swing phase of the arm-swing (100%). This resulted in an overall shorter time spent in the arm up-swing phase during arm-swing countermovement condition (0.0926 s) compared to no arm-swing countermovement (0.1032 ± 0.02 s), reinforcing that the arm-swing countermovement had had a positive impact upon the early concentric phase of the arm-swing. Furthermore, the findings from study two suggest that a further increase in the arm-swing countermovement could be translated into additional improvements in the subsequent concentric phase of the arm-swing, which supports the case for athletes that are training to increase their jump height to include specific attention to the arm-swing countermovement training. Moreover, the main type of exercise prescribed for training a countermovement is plyometrics, which is a specific type of exercise that aims to improve an athlete's ability to use the stretch shortening cycle (SSC), by utilising an increase in muscle pre-stretch that is developed during an increased countermovement (Marinho et al., 2010). This develops a faster arm-swing during the subsequent concentric performance, indicating that the arm-swing countermovement could benefit from plyometric exercise (Toumi et al., 2004; Lephart et al., 2005).

The main aim for study 3 was to ascertain if upper-extremity plyometric exercises could be utilised by elite basketball players to increase their jump height. However, initially the arm-swing during vertical jumping was examined in an attempt to identify the optimal arm-swing conditions during the forward arm-swing movement. Part 1 to Study 3 demonstrated the use of a large AROM arm-swing during the arm-swing countermovement was the optimal arm-swing condition for increasing arm-swing kinematics. Furthermore, an increase in eccentric load during the arm-swing performance trials (90° start position) was shown to increase peak arm-swing kinematics. Interestingly, the increase in shoulder AROM during the large AROM (back-swing) arm-swings and the subsequent increase in peak concentric shoulder ω, suggested that as eccentric loading increased, the subsequent concentric movement also increased, which according to the work by Moran et al. (2007), indicates greater utilisation of the SSC. Conversely, the arm-swings utilising smaller eccentric loads, such as a 70° arm-swing start position coupled with a decrease in arm-swing AROM (short and medium back-swing), resulted in a decrease in peak concentric shoulder ω, reflected by the lowest peak concentric shoulder ω values (479.7 and 497.1 $deg \cdot s^{-1}$) observed during the 84 45 short and 67 45 short arm-swing conditions. This was further evidence for the important role of the arm-swing countermovement during vertical jumping.

An important and unexpected finding in Part 1 of Study 3 was observed upon closer examination of peak shoulder ω in the frontal and transverse planes. That is, it emerged that the arm-swing during vertical jumping is a highly active multi-planar movement, and not solely located within the sagittal plane of motion (flexion and extension) as previously alluded to (Lees et al., 2004; Feltner et al., 2004). The frontal plane movement relates to abduction and adduction of the arm during the latter stages of the arm-swing countermovement and early stages of the concentric arm-swing, respectively. This indicates a movement produced using different muscle groups than that used to create shoulder flexion, and this had not been considered prior to this study. However, the fact that the frontal plane movement is inherent within upper-extremity mechanics, training the arm-swing using movement-specific upper-extremity plyometric exercises would be a good recommendation for a programme to incorporate. This should ultimately lead to an even greater increase in concentric arm-swing kinematics.

The main findings in this study revealed that the use of an upper-extremity plyometric training programme significantly increased the mean jump height (+ 7.2 cm), mean peak shoulder ω (+ 167.1 deg·s^{-1}), mean peak frontal shoulder ω (+ 121 deg·s^{-1}) and mean AROM at the shoulder joint (+ 5.3 °). The increase in peak shoulder ω (+ 167.1 deg·s^{-1}) yielded an absolute peak value of -789.9 ± 96.9 deg·s^{-1}, which, given that all the other joints in the vertical jump kinematic chain demonstrated no significant change in peak ω, suggests that the increase in jump height (7.2 cm) for the upper-extremity plyometric group was directly due to the increase in arm-swing velocity. Notably, a significant contributor to the increase in peak concentric shoulder ω was the was the use of an arm-swing countermovement, which indicated a kinematic link between the increase in eccentric arm-swing movement, followed by the increase in the subsequent concentric arm movement and the overall increase in jump height. Moreover, this suggests that upper-extremity plyometric exercises train both the eccentric and concentric phases of the arm-swing during vertical jumping, and the use of an upper-extremity plyometric programme for training the arm-swing to increase vertical jump performance should be advocated.

The primary mechanisms responsible for increasing vertical jump height and the concentric phase of the arm-swing were attributed to the participants' improved ability to utilise the SSC, which would have developed as a response to an increase in muscle pre-stretch. Furthermore, this would have also increased facilitation from the elastic energy transfer system (Lees et al., 2006), stretch reflex system (Komi et al., 1997) and the contractile components (Binder-McCleod et al., 2002; Bobbert et al., 2005), which were all acknowledged during study two as contributing factors to the increase in concentric performance of a movement when it is preceded by a countermovement. The SSC appears to demonstrate the same response to an increased countermovement in the upper-extremities as previously demonstrated in the lower-extremities (Moran et al., 2007), indicating that the eccentric phase of upper-extremity countermovement's in sport should also be trained using plyometric type exercises. This develops further rationale for advocating the use of upper-extremity plyometric exercises for increasing vertical jump performance.

Collectively, the three studies undertaken throughout this thesis have explored the role of the arm-swing countermovement during vertical jumping and in each case have enabled the conclusion that an increase in arm-swing velocity and an increase in the countermovement of the arm-swing effectively create an increase in vertical jump performance. Overall, this led to the development of an upper-extremity plyometric programme that was designed specifically to increase the kinematics of the arm-swing. Moreover, the final study in this thesis showed that the use of such a programme significantly increased mean peak shoulder ω (+ 167.1 $\text{deg}\cdot\text{s}^{-1}$), mean peak frontal shoulder ω (+ 121 $\text{deg}\cdot\text{s}^{-1}$) and mean AROM at the shoulder joint (+ 5.3°), leading to a significant increase in jump height (+ 7.2 cm). Therefore, the use of upper-extremity plyometrics to increase vertical jump performance is supported.

6.2 Limitations

The main limitation within the first two studies of this thesis was the use of 2D video analysis. This became apparent following an unexpected finding during Part 2 in Study 3 when the 3D analysis revealed the arm-swing during vertical jumping to be a multi-planar movement, and not solely located within the sagittal plane as previously described (Lees et al., 2004; Feltner et al., 2004). Furthermore, the peak shoulder ω values observed during the 3D analysis appear to underestimate those that are analysed in 2D or vice versa, partly due to the movement in the frontal plane not be detected by the 2D analysis, and therefore increasing the value for peak arm-swing velocity in the sagittal plane.

A second limitation within this programme of research was the attempt to analyse a sporting movement (arm-swing) that is part of a kinematic chain in isolation. Securing segments that are normally moving during a vertical jump (such as the trunk), and then observing the arm-swing during this altered movement is a threat to the ecological validity of the current research, and is possibly reflected by the increase in arm-swing velocity observed during the vertical jumps not being apparent during the performance arm-swing trials. However, single moving segments that move as part of a kinematic chain are very complicated to analyse, and different methods of analysis for kinematic chain movements requires further exploration.

A further limitation to this study was that the upper-extremity plyometric programme did not include any frontal plane exercises. Although the mean peak value for each frontal plane movement was less than the mean peak value for each sagittal plane movement, suggesting that shoulder flexion is used more than shoulder adduction during the arm-swing in vertical jumping, the values were still high enough to indicate that the arm-swing is a multi-planar movement. This indicates that the frontal plane movement should be trained using the same techniques as used in the sagittal plane, and therefore, future studies should also include upper-extremity plyometric exercises that train the frontal aspect of the arm-swing movement during vertical jumping, as this could lead to even greater gains in arm-swing velocity and jump height.

6.3 Future directions

Study three only examined a homogenous group of elite male basketball players to ascertain their kinematic response to upper-extremity plyometric training, and considering the positive results that emerged, future studies could focus on different samples, such as sub-elite male, junior, female and mixed populations. Furthermore, different jumping sports which use countermovements, such as volleyball and the high jump in athletics, could be scrutinised for their response to upper-extremity plyometric training.

In addition, on the basis of pilot work carried out during the first study in this thesis, the use of an upper-extremity countermovement was identified in tennis serving and the squash forehand, and could be worth investigating. However, one of the major problems with developing movement-specific upper-extremity plyometric exercises for these movements is their complexity, as both demonstrate a multi-planar sequence of rotating body segments. Furthermore, individual differences in technique would make a generic set of upper-extremity plyometric exercises not suitable for everyone. Moreover, variations in the type of serve action (slice, top-spin, flat) make this challenge even more complex. An example of the complexity of the movement pattern for the tennis serve is shown in a sagittal plane view in Figure 6.1.

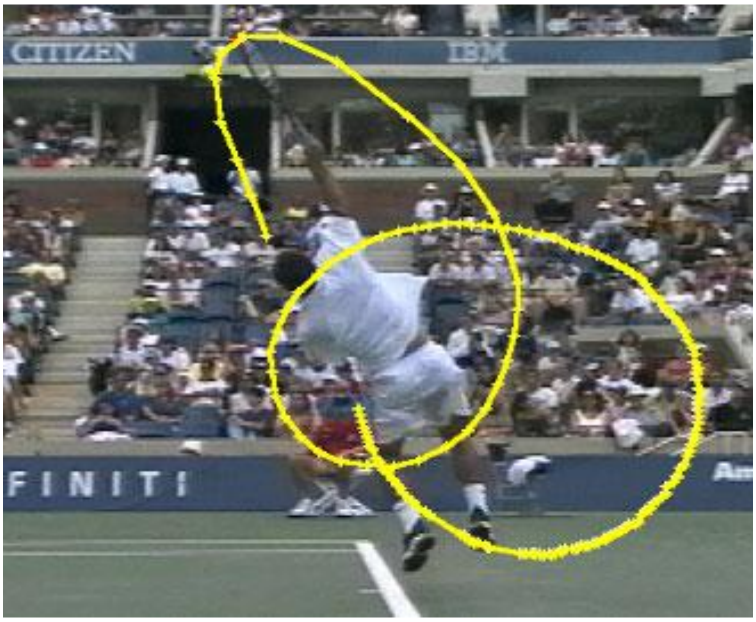


Figure 6.1 Movement pattern trace for shoulder during the tennis serve

The full movement comprises a sequence of tri-planar movements at the shoulder, occurring simultaneously around the trunk which is also rotating. Nonetheless, the pattern shows an arm-swing countermovement during the cross-over section of the middle yellow circle within the trace, as the shoulder changes the movement of the arm from internal to external shoulder rotation. The countermovement observed in Figure 6.1 picture suggests that part of the tennis serve could also be trained using an upper-extremity plyometric training programme, and warrants further investigation in a future study.

The use of electromyography (EMG) and force time curves, coupled with 3D analysis would have been a welcomed addition during study 3 of this thesis, and possibly help ascertain a better understanding of the vertical jump. A detailed analysis of force time curves would have allowed force variables such as the rate of force development, instantaneous force, average and peak force. Furthermore, this would allow a greater exploration of the braking and propulsive elements of the SSC during vertical jumping. Additionally, the use of EMG to analyse multi-planar movements could help identify which muscle group is acting as the prime mover throughout movements occurring in more than one plane simultaneously. An attempt to collect EMG data was performed in Studies 3 and 4, however, during the post-test analyses it emerged that certain diagnostic problems rendered the data unusable. Therefore, the use of EMG, force and 3D analysis should also be considered in future studies in this area, and warrants further investigation.

The observed multi-planar movements in study 3 of this thesis also merit further exploration, and the development of frontal and transverse plane plyometric exercises need to be considered for future studies in this area. Furthermore, the current thesis only examined the kinematics of the arm-swing during the vertical jump after completion of an upper-extremity plyometric programme, which in future, could be combined with a lower-extremity programme. Moreover, lower-extremity and upper-extremity plyometric programmes could be compared directly to see which yields the greatest increase in jump height, and these could then be cross-examined against a programme comprised of both. An upper-extremity plyometric programme composed of different variations of duration, frequency, volume and recovery could also be examined, involving different types of exercise that include weighted and resistance exercises. All these combinations could possibly help identify the optimal variation of training for increasing sport-specific performance. Modalities of training have improved widely over the last ten years with athletes striving to gain every possible advantage in their sports. These training methods have included vibration training, periodisation training, electrostimulation training, golgi-tendon-organ training and various plyometric exercises. However, if these training methods are not utilised correctly, such as choosing to use a sub-maximal, high volume plyometric programme in place of a high-intensity, maximal effort, low frequency and low volume plyometric programme, then the overall result may be a complete waste of athlete and coach time. The key findings in this thesis have shown that significant increases in vertical jump height can be achieved in minimal time when using a well planned high-intensity plyometric programme.

CHAPTER 7

REFERENCES

Adams, K., O'Shea, J.P., O'Shea, K.L., & Climstein, M. (1992). The effect of six weeks of squat, plyometric and squat-plyometric training on power production. *Journal of Applied Sport Science Research, 6* (1), 36-41.

Adhikari, M., & Kanchan. (2011). Effect of plyometric training on arm and leg strength between basketball and volleyball players. *VSRD Technical and Non-Technical Journal, 2* (9), 413-423.

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

Arabatzi, F., Kellis, E., & Villarreal, S. (2010). Vertical jump biomechanics after plyometric, weightlifting, and combined (weight lifting + plyometric) training. *Journal of Strength and Conditioning Research, 24* (9), 2440-2448.

Ashby, B.M., & Delp, S.L. (2005). Optimal control simulations reveal mechanisms by which arm movement improves standing long jump performance. *Journal of Biomechanics, 39* (9), 1726-1734.

Ashby, B.M., & Heegaard, J.H. (2002). Role of arm motion in the standing long jump. *Journal of Biomechanics, 35,* 1631-1637.

Asmussen E, & Bonde-Peterson, F. (1974). Storage of elastic energy in skeletal muscles in man. *Acta Physiologica Scandinavica, 91,* 385-392.

Bartlett, R. (2007). *Introduction to sports biomechanics: Analysing human movement patterns*. New York: Routledge.

Binder-Macleod, S.A., Dean, J.C., & Ding, J. (2002). Electrical stimulation factors in potentiation of human quadriceps femoris. *Muscle and Nerve, 25*, 271-279.

Bishop, D.C., & Wright, C. (2006). A time-motion analysis of professional basketball to determine the relationship between three activity profiles: high, medium and low intensity and the length of the time spent on court. *International Journal of Performance Analysis in Sport, 6* (1), 130-139.

Benoit, D.L., Dowling, J.J. (2006). In vivo assessment of elbow flexor work and activation during stretch-shortening cycle tasks. *Journal of Electromyography and Kinesiology, 16* (4), 352-364.

Biewener, A.A. (1997). Effects of elastic energy storage on muscle work and efficiency. *Journal of Applied Sports Biomechanics, 13* (4), 422-425.

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

Bobbert, M.F., & Casius, L.J.R. (2005). Is the effect of a countermovement on jump height due to active state development? *Medicine and Science in Sports and Exercise, 37* (3), 440-446.

Bobbert, M.F., Casius, L.J.R., Sijpkins, I.W.T., & Jaspers, R.T. (2008). Humans adjust control to initial squat depth in vertical squat jumping. *Journal of Applied Physiology, 105* (5), 1428-1440.

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

Bobbert, M.F., Huijing, P.A., & Ingen-Schenau, G.J.V. (1986). An estimation of power output and work done by the human triceps surae musle-tendon complex in jumping. *Journal of Biomechanics, 19* (11), 899-906.

Bobbert, M.F., Huijing, P.A., Ingen Schenau, G.J.V. (1987a). Drop jumping. I. The influence of jumping technique on the biomechanics of jumping. *Medicine and Science in Sports and Exercise, 19* (4), 332-338.

Bobbert, M.F., Huijing, P.A., Ingen Schenau, G.J.V. (1987b). Drop jumping. II. The influence of dropping height on the biomechanics of drop jumping. *Medicine and Science in Sports and Exercise, 19* (4), 339-346.

Bobbert, M.F., & Van-Zandwijk, J.P. (1999). Dynamics of force and muscle stimulation in human vertical jumping. *Medicine & Science in Sports & Exercise, 31* (12), 303-310.

Bosco, C., Komi, P.V., & Ito, A. (1981). Prestretch potentiation of human skeletal muscle during ballistic movement. *Acta Physiologica Scandinavica, 111* (2), 135-140.

Bosco, C. (1997). The effect of prestretch on skeletal muscle behaviour. *Journal of Applied Biomechanics, 13* (4), 426-429.

Bosco, C., & Komi, P.V. (1979). Potentiation of the mechanical behaviour of the human skeletal muscle through prestretching. *Acta Physiologica Scandinavica, 106* (4), 467-472.

Brodt, V., Wagner, D.R., & Heath, E.M. (2008). Countermovement vertical jump with drop step is higher than without in collegiate football players. *Journal of Strength and Conditioning Research, 22* (4), 1382-1385.

Carter, A.B., Kaminski, T.W., Douex Jnr, A.T., Knight, C.A., & Richards, J.G. (2007). Effects of high volume upper extremity plyometric training on throwing velocity and functional strength ratios of the shoulder rotators in collegiate baseball players. *Journal of Strength and Conditioning Research, 21* (1), 208-215.

Cavagna, G.A, Dusman, B., & Margaria, R. (1968). Positive work done by a previously stretched muscle. *Journal of Applied Physiology, 24* (1), 21-32.

Cavagna, G.A, Komarek, Cittero & Margaria, (1971). Power output of the previously stretched muscle. *Medicine and Sport, 6*, 159 – 167.

Cavagna, G.A., Saibene, F.P., & Margaria, R. (1965). Effect of negative work on the amount of positive work performed by an isolated muscle. *Journal of Applied Physiology, 20* (1), 157-158.

Chin, A., Elliott, B., Alderson, J., Lloyd, D., & Foster, D. (2009) The off-break and "doosra": Kinematic variations of elite and sub-elite bowlers in creating ball spin in cricket bowling. *Sports Biomechanics, 8* (3), 187-198.

Chmielewski, T.L., Myer, D., Kauffman, D., & Tillman, S.M. (2006). Plyometric exercise in the rehabilitation of athletes: Physiological responses and clinical application. *Journal of Orthopaedic & Sports Physical Therapy, 36* (5), 308-319.

Chu, D.A. (1983). Plyometrics: the link between strength and speed. *National Strength and Conditioning Association Journal, 5* (2), 20-21.

Chu, D.A., & Plummer, L. (1984). Jumping into plyometrics: the language of plyometrics. *National Strength and Conditioning Association Journal, 6* (5), 30-31.

Chu, D.A. (1998). *Jumping into plyometrics: A learners manual.* Leeds: Human Kinetics.

Clutch, D. (1983). The effect of depth jumps and weight training on leg strength and vertical jump. *Research Quarterly for Exercise and Sport, 54* (1), 5-10.

Dapena, J. (1993). Biomechanical studies in the high jump and implications for coaching. *Modern Athlete and Coach, 31*(4), 7–12.

Diallo, O., Dore, E., Duche, P., & Van Praagh, E. (2001). Effects of plyometric training followed by a reduced training programme on physical performance in prepubescent soccer players. *Journal of Sports Medicine and Physical Fitness, 41* (3), 342-348.

Dietz, V., Schmidtbleicher, D., & Noth. J. (1979). Neuronal mechanisms of human locomotion. *Journal of Neurophysiology, 42* (5), 1212-1222.

Doan, B.K., Newton, R.U., Marsit, J.L., Triplett-McBride, N.T., Fry, A.C., & Kraemer, W.J. (2002). Effects of increased eccentric loading on bench press 1RM. *Journal of Strength and Conditioning Research, 16* (1), 9-13.

Earp, J.E., Kraemer, W.J., Newton, R. U., Comstock, B.A., Fragala, M.S., Dunn-Lewis, C., Solomon-Hill, G., Penwell, Z.R., Powell, M.D., Volek, J.S., Denegar, C.R., Hakkinen, K., & Maresh, C.M. (2010). Lower body muscle structure and its role in jump performance during squat, countermovement and depth drop jumps. *Journal of Strength and Conditioning Research, 24* (3), 722-729.

Ebben, W.P., Flanagan, E.P., & Jensen, R.L. (2008). Jaw clenching results in concurrent activation potentiation during the countermovement jump. *Journal of Strength and Conditioning Research, 22* (6), 1850-1854.

Ebben, W,P., Simenz, C., & Jensen, R.L. (2008). Evaluation of plyometric intensity using electromyography. *Journal of Strength and Conditioning Research, 22* (3), 861-868.

Edman, K.A., Elzinga, G., &Noble, M.I. (1982). Residual force enhancement after stretch of contracting frog single muscle fibers. *The Journal of General Physiology, 80* (5), 769-784.

Ellenbecker, T.S., Roetert, E.P., Bailie, D.S., Davies, G.J., & Brown, S.W. (2002). Glenohumeral joint total rotation range of motion in elite tennis players and baseball pitchers. *Medicine and Science in Sports and Exercise, 34* (12), 2052-2056.

Elliot, B., & Alderson, J. (2007). Laboratory versus field testing in cricket bowling: A review of current and past practice in modelling techniques. *Sports Biomechanics, 6* (1), 99-108.

Elliot, B., Fleisig, G., Nicholls, R., & Escamilla, R, (2003). Technique effects on upper limb loading in the tennis serve. *Journal of Science and Medicine in Sport, 6* (1), 76-87.

Elliot, B., Marshall, R., & Noffal, G. (1996). The role of upper limb segment rotation in the development of racket head speed in the squash forehand. *Journal of Sports Sciences, 14,* 159-156.

Escamilla, R.F., Fleising, G.S., Yamashiro, K., Mikla, T., Dunning, R., Paulos, L., & Andrews, J.R. (2010). Effects of a 4-week youth baseball conditioning programme on throwing velocity. *Journal of Strength and Conditioning Research, 24* (12), 3247-3254.

Ettema, G.J.C. (1996). Mechanical efficiency of storage and release of series elastic energy in skeletal muscle during stretch-shorten cycles. *The Journal of Experimental Biology, 199,* 1983-1997.

Ettema, G.J.C. (2001). Muscle efficiency: the controversial role of elasticity and mechanical energy conversion in stretch-shortening cycles. *European Journal of Applied Physiology, 85,* 457-465.

Farley, C.T., & Ko, T.C. (1997). Mechanics of locomotion in lizards. *The Journal of Experimental Biology, 200,* 2177-2188.

Fatouros, I.G., Jamurtas, A.Z., Leontsini, D., Taxildaris, K., Aggelousis, N., Kostopoulos, N., & Buckenmeyer, P. (2000). Evaluation of plyometric exercise training, weight training, and their combination on vertical jumping performance and leg strength. *Journal of Strength and Conditioning Research, 14* (4), 470-476.

Faul, F., Erdfelder, E., Lang, A.G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis programme for the social, behavioural, and biomedical sciences. *Behaviour Research Methods, 39* (2), 175-191.

Feltner, M.E., Fraschetti, D.J., & Crisp, R.J. (1999). Upper extremity augmentation of lower extremity kinetics during countermovement vertical jumps. *Journal of Sports Sciences, 17,* 449-466.

Feltner, M.E., Bishop, E.J., & Perez, C.M. (2004). Segmental and kinetic contributions in vertical jumps performed with and without an arm swing. *Research Quarterly for Exercise and Sport, 75* (3), 216-230.

Fletcher, I.M., & Hartwell, M. (2004). Effect of an 8-week combined weights and plyometrics training programme on golf drive performance. *Journal of Strength & Conditioning Research, 18* (1), 59-62.

Flitney, F.W., & Hirst, D.G. (1978). Cross-bridge detachment and sarcomere 'give' during stretch of active frog's muscle. *The Journal of Physiology, 276,* 449-465.

Fortun, C., Davies, G., & Kernozek, T. (1998). The effects of plyometric training on the shoulder internal rotators. *Journal of Physical Therapy, 78* (51), 63-75.

Fowler, N., Trzaskoma, Z., Wit, A., Iskra, L., & Lees, A. (1995). The effectiveness of a pendulum swing for the development of leg strength and counter-movement jump performance. *Journal of Sports Sciences, 13* (2), 101-108.

Fukashiro, s., Fukunaga, T., Ichinose, Y., Ito, M., & Kawakami, Y. (1997). Determination of fascile length and pennation in a contracting human muscle in vivo. *Journal of applied physiology, 82* (1), 354-358.

Gamble, P. (2010). *Strength and conditioning for team sports:* Sport specific physical preparation for high performance. Routledge: London.

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 Research, 12* (2), 85-89.

Gerodimos, V., Zafeiridis, A., Perkos, S., Dipla, K., Manou, V., & Kellis, S. (2008). The contribution of stretch-shortening cycle and arm swing to vertical jumping performance in children, adolescents and adult basketball players. *Pediatric Exercise Sciences, 20,* 379-389.

Gollhofer, A., Strojnik, V., Rapp, W., & Schweizer, L. (1992). Behaviour of triceps surae muscle-tendon complex in different jump conditions. *European Journal of Applied Physiology and Occupational Physiology, 64* (4), 283-291.

Hakkinen, K., Alen, M., & Komi, P.V. (1985). Changes in isometric force- and relaxation-time, electromyographic and muscle fibre characteristics of human skeletal muscle during strength training and detraining. *Acta Physiologica Scandinavica, 125* (4), 573-585.

Hamill, J., & Knutzen, K.M. (2003). *Biomechanical Basis of Human Movement.* Baltimore: Lippincott Williams and Wilkins.

Hamill, J., & Knutzen, K.M. (2009). *Biomechanical Basis of Human Movement; 2nd edition.* Baltimore: Lippincott Williams and Wilkins.

Hamill, J., & Knutzen, K.M. (2010). *Biomechanical Basis of Human Movement; 3rd edition.* Baltimore: Lippincott Williams and Wilkins.

Hara, M., Shibayama, A., Takeshita, D., & Fukashiro, S. (2006). The effect of arm swing on lower extremities in vertical jumping. *Journal of Biomechanics, 39,* 2503-2511.

Hara, M., Shibayama, A., Takeshita, D., Hay, D.C., & Fukashiro, S. (2008). A comparison of the mechanical effect of arm swing and countermovement on the lower extremities in vertical jumping. *Human Movement Science, 27,* 636-648.

Harrison, A.J., Keane, S.P., & Coglan, J. (2004). Force-velocity relationship and stretch-shortening cycle function in sprint and endurance athletes. *Journal of Strength & Conditioning Research, 18* (3), 473-479.

Havalee, T.H., Ellerby, D.J., & Marsh, R.L. (2005). Performance of guinea fowl *Numida meleagris* during jumping requires storage and release of elastic energy. *The Journal of Experimental Biology, 208*, 3293-3302.

Hay, J.G., & Reid, J.G. (1998). *Anatomy, mechanics and human motion.* Englewood Cliffs, NJ: Prentice Hall.

Hennessy, L., & Kilty, J. (2001). Relationship of the Stretch-Shortening Cycle to sprint performance in trained female athletes. *Journal of Strength & Conditioning Research, 15* (3), 326-331.

Herrero, J.A., Izquierdo, M., Maffiuletti, N.A., & Lopez, G.J. (2006). Electromyostimulation and Plyometric Training Effects on Jumping and Sprint Time. *International Journal of Sports Medicine, 27,* (7), 533-539.

Holcomb, W.R., Lander, J.E., Rutland, R.M., & Wilson, D. (1996a). The effectiveness of a modified plyometric programme on power and the vertical jump. *Journal of Strength and Conditioning Research, 10* (2), 89-92.

Holcomb, W.R., Lander, J.E., Rutland, R.M., & Wilson, D. (1996b). A bio-mechanical analysis of the vertical jump and three modified plyometric depth jumps. *Journal of Strength and Conditioning Research, 10* (2), 83-88.

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

Impellizzeri, F.M., Rampinini, E., Castagna, C., Martino, F., Fiorini, S., & Wisloff, U. (2008). Effect of plyometric training on sand versus grass on muscle soreness and jumping and sprinting ability in soccer players. *British Journal of Sports Medicine, 42* (1), 42-46.

Ingen Schenau, G.J., Bobbert, M.F., & De Haan, A. (1997a). Does elastic energy enhance work and efficiency in the stretch-shortening cycle? *Journal of Applied Biomechanics, 13,* 389- 415.

Ingen Schenau, G.J., Bobbert, M.F., & De Haan, A. (1997b). Mechanics and energetic of the stretch-shortening cycle: a stimulating discussion. *Journal of Applied Biomechanics, 13,* 484-496.

Innocenti, B., Facchielli, D., Torti, S., & Verza, A. (2006). Analysis of biomechanical quantities during a squat jump: evaluation of a performance index. *Journal of Strength & Conditioning Research, 20* (3), 709-715.

Ishikawa, M., Niemala, E., & Komi, P.V. (2005). Interaction between fascicle and tendinous tissues in short-contact stretch-shortening cycle exercise with varying eccentric intensities. *Journal of Applied Physiology, 99* (1), 217-223.

Jensen, R.L., & Ebben, W.P. (2007). Quantifying plyometric intensity via rate of force development, knee joint, and ground reaction forces. *Journal of Strength & Conditioning Research, 21* (3), 763-767.

Kay, D., Mitchell, M.J., Lambert, M.I., & Noakes, T.D. (2000). Different neuromuscular recruitment patterns during eccentric, concentric and isometric contractions. *Journal of Electromyography and Kinesiology, 10* (6), 425-431.

Khlifa, R., Aouadi, R., Hermassi, S., Chelly, M.S., Jlid, M.C., Hbacha, H., & Castagna, C. (2010). Effects of a plyometric training programme with and without added load on jumping ability in basketball players. *Journal of Strength & Conditioning Research, 24* (11), 2955-2961.

King, J.A., & Cipriani, D.J. (2010). Comparing preseason frontal and sagittal plane plyometric programmes on vertical jump height in high school basketball players. *Journal of Strength & Conditioning Research, 24* (8), 2109-2114.

Klinzing, J.E. (1991). Training for improved jumping ability of basketball players. *Journal of Strength & Conditioning Research, 24* (8), 2109-2114.

Komi, P.V. (2000). Stretch-shortening cycle: a powerful model to study normal and fatigued muscle. *Journal of Biomechanics, 33*, 1197-1206.

Komi, P.V., & Bosco, C. (1978). Utilization of stored elastic energy in leg extensor muscles by men and women. *Medicine and Science in Sports, 10* (4), 261-265.

Komi, P.V., & Gollhofer, A. (1997). Stretch reflexes can have an important role in force enhancement during SSC exercise. *Journal of Applied Biomechanics, 13* (4), 451-459.

Knudson, D. (2003). *Fundamentals of biomechanics.* New York: Kluwer Academic/ Plenum Publishers.

Kubo, K., Kawakami, Y., & Fukunaga, T. (1999). Influence of elastic properties of tendon structures on jump performance in humans. *Journal of Applied Physiology, 87* (6), 2090-2096.

Laffaye, G., Bardy, B.G., & Durey, A. (2005). Leg stiffness and expertise in men jumping. *Medicine and Science in Sports and Exercise, 37* (4), 536-543.

Lees, A., & Barton, G. (1996). The interpretation of relative momentum data to assess the contribution of the free limbs to the generation of vertical velocity in sports activities. *Journal of Sports Sciences, 14,* 503-511.

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

Lees, A., Rojas, J., Cepero, M., Soto, V., & Guierrez, M. (2000). How the free limbs are used by elite high jumpers in generating vertical velocity. *Ergonomics, 43* (10), 1622-1636.

Lees, A., Vanrenterghem, J., & De Clercq, D. (2004). Understanding how an arm swing enhances performance in the vertical jump. *Journal of Biomechanics, 37,* 1929-1940.

Lees, A., Kemp, M., & Moura, F. (2005). *A biomechanical analysis of the soccer throw-in with a particular focus on the upper limb motion.* Science and Football V: The Proceedings of the Fifth World congress of science and football, Routledge, London.

Lees, A., Vanrenterghem, J., & De Clercq, D. (2006). The energetics and benefit of an arm swing in submaximal and maximal vertical jump performance. *Journal of Sports Sciences, 24* (1), 51-57.

Lephart, S.M., Abt, J.P., Ferris, C.M., Sell, T.C., Nagai, T., Myers, J.B., & Irrang, J.J. (2005). Neuromuscular and biomechanical characteristic changes in high school athletes: a plyometric versus basic resistance programme. *British journal of sport medicine, 39,* 932-938.

Lichtwark, G.A., Bougoulias, K., & Wilson, A.M. (2007). Muscle fascicle and series elastic element length changes along the length of the human gastrocnemius during walking and running. *Journal of Biomechanics, 40* (1), 157-164.

Lloyd, D.G., Alderson, J., & Elliot, B.C. (2000). An upper limb kinematic model for the examination of cricket bowling: A case study of Mutiah Muralitharan. *Journal of Sports Sciences*, *18,* 975-982.

Luebbers, P.E., Potteiger, J.A., Hulver, M.W., Thyfault, J.P., Carper, M.J., & Lockwood, R.H. (2003). Effects of plyometric training and recovery on vertical jump performance and anaerobic power. *Journal of Strength and Conditioning Research, 17* (4), 704-709.

Luhtanen, P., & Komi, R.V. (1978). Segmental contribution to forces in vertical jump. *European Journal of Applied Physiology and Occupational Physiology, 38* (3), 181-188.

Luhtanen, P., & Komi, R.V. (1979). Mechanical power and segmental contribution to force impulses in long jump take-off. *Journal of Applied Physiology and Occupational Physiology, 41* (4), 267-274.

Maffiuletti, N.A., Dugnani, S., Folz, E., Di Pierno, E., & Maura, F. (2002). Effect of combined electrostimulation and plyometric training on vertical jump height. *Medicine and Science in Sports and Exercise, 34* (10), 1638-1644.

Markovic, G. (2007). Does plyometric training improve vertical jump height? A meta-analytic review. *British Journal of Sport Medicine*, *DOI* 10:1136/ bjsm.2007.035113.

Markovic, G., & Jaric, S. (2007). Is vertical jump height a body size-dependent measure of muscle power? *Journal of Sports Sciences, 25* (12), 1355-1363.

Markovic, G., & Jaric, S. (2007). Positive and negative loading and mechanical output in maximum vertical jumping. *Medicine and Science in Sports and Exercise, 39* (10), 1757-1764.

Markovic, G., Jukic, I., Milanovoc, D., & Metikos, D. (2007). Effects of sprint and plyometric training on muscle function and athletic performance. *Journal of Strength & Conditioning Research, 21* (2), 543-549.

Marques, M., Marinho, D., Van der Tillaar, R., Vescovi, J., Gonzalez-Badillo, J. (2008). Changes in strength and power performance in elite senior female professional volleyball players during the in-season: A case study. *Journal of Strength & Conditioning Research, 22* (4), 1147-1155.

Marques, M., Marinho, D., & Van der Tillaar, R. (2010). A load-velocity relationship for men and women in overhead throwing performance. *Journal of sports science and medicine,* (9), 524-526.

Marshall, R.N., & Elliot, B.C. (2000). Long axis rotation: The missing link in proximal-to-distal segmental sequencing. *Journal of Sports Sciences, 18* (4), 247-254.

McBride, J. M., McCaulley, G.O., & Cormie, P. (2008). Influence of preactivity and eccentric muscle activity on concentric performance during vertical jumping. *Journal of Strength & Conditioning Research, 22* (3), 750-757.

Miller, M.G., Berry, D.C., Bullard, S. & Gilders, R. (2002). Comparisons of land-based and aquatic based plyometric programmes during an 8-week training period. *Journal of Sports Rehabilitation, 11,* 269-283.

Miller, M.G., Herniman, J.J., Ricard, M.D., Cheatham, C.C., & Michael, T.J. (2006) The effects of a 6-week plyometric training programme on agility. *Journal of Sports Science and Medicine, 5,* 459-465.

Minetti, A., Narici, M., & Cerretelli, P. (1997). Comments on the role of elastic energy in jumping performance. *Journal of Applied Biomechanics 13* (4), 463-464.

Miyaguchi, K., & Demura, S. (2008). Muscle power output properties using the stretch-shortening cycle of the upper limb and their relationships with a one-repetition maximum bench press, *Journal of Physiological Anthropology, 25* (3), 239-245.

Miyaguchi, K., & Demura, S. (2008). Relationships between muscle power output using the stretch-shortening cycle and eccentric maximum strength. *Journal of Strength & Conditioning Research, 22* (6), 1735-1741.

Miyaguchi, K., & Demura, S. (2008). Relationships between stretch-shortening cycle performance and maximum muscle strength. *Journal of Strength & Conditioning Research, 22* (1), 19-24.

Miyamoto, N., Wakahara, T., Sugisaki, N., Murata, K., Kanehisa, H., Fukunaga, T., & Kawakami, Y. (2010). Effect of countermovement on elbow joint extension power-load characteristics. *Journal of Sports Sciences, 28* (14), 1535-1542.

Moore, C.A., Weiss, L.W., Schilling, B.K., Fry, A.C., & Li, Y. (2007). Acute effects of augmented eccentric loading on jump squat performance. *Journal of Strength & Conditioning Research, 21* (2), 372-377.

Moran, K.A., & Wallace, E.S. (2007). Eccentric loading and range of knee joint motion effects on performance enhancement in vertical jumping. *Human Movement Science, 26,* 824-840.

Myer, G.D., Ford, K.R., Brent, J.L., & Hewett, T.E. (2006). The effects of plyometric vs. dynamic stabilization and balance training on power, balance, and landing force in female athletes. *Journal of Strength & Conditioning Research, 20* (2), 345-353.

Newton, R. U., Murphy, A.J., Humphries, B.J., Wilson, G.J., Kraemer, W.J., & Hakkinen, K. (1997). Influence of load and stretch shortening cycle on the kinematics, kinetics and muscle activation that occurs during explosive upper-body movements. *European Journal of Applied Physiology and Occupational Physiology, 75* (4), 333-342.

Niederbracht, Y., Shim, A.L., Slongier, M.A., Paternostro-Bayles, M., & Short, T.H. (2008). Effects of a shoulder injury prevention strength training programme on eccentric external rotator muscle strength and glenohumeral joint imbalance in female overhead activity athletes. *Journal of Strength & Conditioning Research, 22* (1), 140-145.

Nicol, C., Avela, J., & Komi, P.V. (2006). The stretch –shortening cycle: a model to study naturally occurring neuromuscular fatigue. *Sports Medicine, 36* (11), 977-999

Payne, A.H., Slater, W.J., & Telford, T. (1968). The use of a force platform in the study of athletic activities. A preliminary investigation. *Ergonomics, 11* (2), 123-143.

Payton, C., & Bartlett, R. (2008). *Biomechanical evaluation of movement in sport and exercise: The British association of sport and exercise science guidelines.* Routledge: New York.

Potteiger, J.A., Lockwood, R.H., Haub, M.D., Dolezal, B.A., Almuzaini, K.S., Schroeder, J.A.N.M., & Zebas, C.J. (1999). Muscle Power and Fiber Characteristics Following 8 Weeks of Plyometric Training. *Journal of Strength and Conditioning Research, 13* (3), 275-279.

Pretz, R. (2004). "Ballistic Six" plyometric training for the overhead throwing athlete. *Strength and Conditioning Journal, 26* (6), 62-66.

Prilutsky, B.I. (1997). Work, energy expenditure, and efficiency of the stretch-shortening cycle. *Journal of Applied Biomechanics, 13* (4), 466-470.

Roca, M., Elliot, B., Alderson, J., & Foster, D. (2006). The relationship between shoulder alignment and elbow joint angle in cricket fast-medium bowlers. *Journal of Sports Sciences, 24* (11), 1127-1135.

Ronnestad, B.R., Kvamme, N.H., Sunde, A., & Raastad, T. (2008). Short term effects of strength and plyometric training on sprint and jump performance in professional soccer players. *Journal of Strength and Conditioning Research, 22* (3), 773-780.

Rubley, M.D., Haase, A.C., Holcomb, W.R., Girouard, T.J., & Tandy, R.D. (2011). The effect of plyometric training on power and kicking distance in female adolescent soccer players. *Journal of Strength and Conditioning Research, 25* (1), 129-134.

Salonikidis, K., & Zafeiridis, A. (2008). The effects of plyometric tennis drills and combined training on reaction, lateral and linear speed, power and strength in novice tennis players. *Journal of Strength and Conditioning Research, 22* (1), 182-191.

Sankey, S.P., Jones, P.A., & Bampouras, T.M. (2008). Effects of two plyometric training programmes of different intensity on vertical jump performance in high school athletes. *Serbian Journal of Sports Sciences, 2* (4), 123-130.

Schmidtbleicher, D, Gollhofer, A., & Frick, U. (1988). Effects of a stretch shortening type training on the performance capability and innervations characteristics of leg extensor muscles. In: *Int. Series on Biomechanics, Biomechanics XI-A*, edited by Groot G, Hollander AP, Huijing PA and Van Ingen Schenau G. Amsterdam: Free University Press, p. 185–189.

Schulte-Edelmann, J.A., Davies, G.J., Kernozek, T.W., & Gerberding, E.D. (2005) The effects of plyometric training of the posterior shoulder and elbow. *Journal of Strength and Conditioning Research, 19* (1), 129-134.

Schwieger, K., & Baca, A. (2002). Quantifying the jump height in vertical jumping with two different evaluation concepts. *International Journal of Performance Analysis in Sport, 2* (1), 44-54.

Semenick, D.M., & Adams, K.O. (1987). The vertical jump: a kinesiological analysis with recommendations for strength and conditioning programming. *National Strength and Conditioning Association Journal, 9* (3), 5-9.

Sheppard, J., Newton, R., & McGuigan, M. (2007). The effect of accentuated eccentric load on jump kinetics in high-performance volleyball players. *Journal of Sports sciences & Coaching, 2* (3), 267-273.

Shetty, A.B., & Etnyre, B.R. (1989). Contribution of arm movement to the force components of a maximum vertical jump. *Journal of Orthopaedic Sports and Physical Therapy, 11* (5), 198-201.

Siegler, J., Gaskill, S., & Ruby, B. (2003). Changes evaluated in soccer-specific power endurance either with or without a 10-week, in-season, intermittent, high-intensity training protocol. *Journal of Strength and Conditioning Research, 17* (2), 379-387.

Spurrs, R.W., Murphy, A.J., & Watsford. (2003). The effect of plyometric training on distance running performance. *European Journal of Applied Physiology, 89,* 1-7.

Stefanyshyn, D.J., & Nigg, B.M. (1998). Contribution of the lower extremity joints to mechanical energy in running vertical jumps and running long jumps. *Journal of Sports Sciences, 16,* 177-186.

Strojnik, V., & Komi, P.V. (1998). Neuromuscular fatigue after maximal stretch-shortening cycle exercise. *Journal of Applied Physiology, 84* (1), 344-350.

Suthakar, K., Annida, D.P., Kanaga, S., & Senthil, N. (2009). Effects of plyometric training on arm and leg strength in tennis and field hockey players. *Research Journal of Physical Education and Sports Science*, *4,* 1-119.

Swanik, K.A., Lephart, S.M., Swanik, C.B., Lephart, S.P., Stone, D.A., & Fu, F.H. (2002). Muscle performance characteristics. *Journal of Shoulder and Elbow Surgery, 11* (6), 579-586.

Takahashi, R. (1992). Power training for judo: plyometric training with medicine balls. *National Strength and Conditioning Association Journal*, *14* (2), 66-71.

Takarada, Y., Hirano, Y., Ishige, Y., & Ishii, N. (1997). Stretch induced enhancement of mechanical power output in human multijoint exercise with countermovement. *The American Physiological Society,* 1749 – 1755.

Thomas, K., French, D., & Hayes, P. (2009). The effect of two plyometric training techniques on muscular power and agility in youth soccer players. *Journal of Strength and Conditioning Research*, *23* (1), 332-335.

Tortora, G.J., & Grabowski, S.R. (2003). *Principles of anatomy and physiology: support and movement of the human body*. John Wiley & Sons: New York.

Toumi, H., Best, T.M., Martin, A., Guyer, S.F., Poumarat, G. (2004). Effects of eccentric phase velocity of plyometric training on the vertical jump. *International Journal of Sport Medicine: Orthopedics and Biomechanics, 25,* 391-398.

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. *International Journal of Sports Medicine, 22,* 605-610.

Treiber, F.A., Lott, J., Duncan, J., Slavens, G., & Davis, H. (1998). Effects of theraband and lightweight dumbbell training on shoulder rotation torque and serve performance in college tennis players. *American Journal of Sports Medicine, 26* (4), 510-515.

Turner, A.M., & Jeffreys, I. (2010). The stretch- shortening cycle: proposed mechanisms and methods for enhancement. *Strength and Conditioning Journal, 32* (4), 87-99.

Turner, A.M., Owings, M., & Schwane, J.A. (2003). Improvement in running economy after 6 weeks of plyometric training. *Journal of Strength & Conditioning Research, 17* (1), 60-67.

Vanezis, A., & Lees, A. (2005). A biomechanical analysis of good and poor performers of the vertical jump. *Ergonomics, 48* (11), 1594-1603.

Vanrenterghem, J., Lees, A., & De Clerq, D. (2008). Effect of forward trunk inclination on joint power output in vertical jumping. *Journal of Strength & Conditioning Research, 22* (3), 708-714.

Vetter, R.E. (2007). Effects of six warm-up protocols on sprint and jump performance. *Journal of Strength & Conditioning Research, 21* (3), 819-823.

Villarreal, E.S.S., González-Badillo, J.J., & Izquierdo, M. (2007). Optimal warm-up stimuli of muscle activation to enhance short and long-term acute jumping performance. *European Journal of Applied Physiology, 100* (4), 393-401.

Villarreal, E.S.S., Gonzalez-Badillo, J.J., & Izquierdo, M. (2008). Low and moderate plyometric training frequency produces greater jumping and sprinting gains compared with high frequency. *Journal of Strength & Conditioning Research, 22* (3), 715-725.

Villarreal, E.S.S., Requena, B., & Newton R.U. (2010). Does plyometric training improve strength performance? A meta-analysis. *Journal of Science and Medicine in Sport and Exercise, 13* (5), 513-522.

Villarreal, E.S.S., Kellis, E., Kraemer, W.J., & Izquierdo, M. (2009). Determining variables of plyometric training for improving vertical jump height performance: a meta-analysis. *Journal of Strength & Conditioning Research, 23* (2), 495-506.

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

Walsh, M.S., Armpatzis, A., Schade, F., & Bruggemann, G.P. (2004). The effect of drop jump starting height and contact time on power, work performed and moment of force. *Journal of Strength & Conditioning Research, 18* (3), 561-566.

Walsh, M.S., Bohm, H., Butterfiled, M.M., & Santhosam, J. (2007). Gender bias in the effects of arms and countermovement on jumping performance. *Journal of Strength & Conditioning Research, 21* (2), 362-366.

Walsh, M.S., Waters, J.A., Bohm, H., & Potteiger, J.A. (2007). Gender bias in jumping kinetics in National Collegiate Athletic Association Division 1 basketball players. *Journal of Strength & Conditioning Research, 21* (3), 958-962.

Wilson, G.J., Murphy, A.J., & Pryor, J.F. (1994). Musculotendinous stiffness stiffness: its relationship to eccentric, isometric and concentric performance. *Journal of Applied Physiology, 76* (6), 2714-2719.

Wu, G., van der Helm, F.C.T., Veeger, H.E.J., Makhsous, M., Van Rpy, P., Anglin, C., Nagels, J., Karduna, A.R., McQuade, K., Wang, X., Werner, F.W., & Buchholz, B. (2005). ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion – Part II: shoulder, elbow, wrist and hand. *Journal of Biomechanics, 38,* 981-992.

Yamauchi, J., & Ishii, N. (2007). Relations between force-velocity characteristics of the knee-hip extension movement and vertical jump performance. *Journal of Strength & Conditioning Research, 21* (3), 703-709.

Young, W.B., Pryor, J.F., & Wilson, G.J. (1995). Effect of instructions on characteristics of countermovement and drop jump performance. *Journal of Strength & Conditioning Research, 9* (4), 232-236.

CHAPTER 8

APPENDICES

University of Chester
Faculty of Applied and Health Sciences
Research Ethics Committee

Appendix 3.31 (ethical approval study 1)

Robert William Connell

16th July 2009

Dear Robert,

Study title: A biomechanical analysis of the arm-swing countermovement during vertical jumping.
FREC reference: 316/09/RC/SES
Version number: 1

Thank you for sending the above-named application to the Faculty of Applied and Health Sciences Research Ethics Committee for review.

The application has been considered by the Faculty Research Ethics Committee.

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form and supporting documentation.

The favourable opinion is given provided that you comply with the conditions set out in the attached document. You are advised to study the conditions carefully.

The final list of documents reviewed and approved by the Committee is as follows:

With the Committee's best wishes for the success of this project.

Yours sincerely,

Mohammed Saeed
Chair, Faculty Research Ethics Committee

Enclosures ***Standard conditions of approval.***
c.c. Supervisor FREC Representative

Appendix 3.32 (Consent form study 1)

Title of project

An investigation into the arm-swing countermovement during vertical jumping.

Name of researcher

Mr. Robbie Connell

Please tick the box if you agree with the statement:

☐ I confirm that I have read and understood the participant information sheet for the above-named study, and have had the opportunity to ask the lead researcher any questions.

☐ I understand that my participation is voluntary, and that I am free to withdraw from participating in the study at any time, without giving any reason and without my rights being affected.

☐ I understand that my participation in this study will be videotaped and I may collect a copy of my performance at the end of the test.

☐ I agree to participate in the above study

☐ I would/would not like to be informed of the results of this study (please delete as appropriate).

Name of participant ________________________

Date ________________________

Signature ________________________

Name of researcher ________________________

Date ________________________

Signature ________________________

Appendix 3.33 (pre-test health questionnaire study 1)
DEPARTMENT OF SPORT AND EXERCISE SCIENCES
UNIVERSITY OF CHESTER

PRE-TEST HEALTH QUESTIONNAIRE

(Please note that this information will be confidential)

Name………………………………………………… DOB……………
Age…………….....

Practical/Project
Title………………………………………………………………………………………

Please answer these questions truthfully and completely. The purpose of this questionnaire is to ensure that you are fit and healthy enough to participate in this laboratory practical/research project.

Yes **No**

1. Have you in the past suffered from a serious illness or accident. ☐ ☐
   If Yes, please provide details.

   ……………………………………………………………………………………………………
   ……………………………………………………………………………………………………
   ……………...

Yes **No**

2. Have you consulted your doctor the last 6 months ☐ ☐
   If Yes, please provide details

……………………………………………………………………………………………………
……………….…………..……………………………………………………………………………
……………………………………………………………

3. Do you suffer, or have you suffered from:

Yes *No*
Asthma ☐ ☐
Diabetes ☐ ☐
Bronchitis ☐ ☐
Epilepsy ☐ ☐
High blood pressure ☐ ☐

Yes **No**

4. Is there any history of heart disease in your family ☐ ☐

Yes **No**

5. Are you suffering from any infectious skin diseases, sores, wounds, or blood infections i.e., Hepatitis B, HIV, etc.? ☐ ☐
If Yes, please provide brief details.
……………………………………………………………………………………………
……………………………………………………………………………………………
………………

Yes **No**

6. Are you currently taking any medication ☐ ☐
If Yes, please provide details.
……………………………………………………………………………………………
……………………………………………………………………………………………
……………………………………………………………………………………………
………………………

Yes **No**

7. Is there anything to your knowledge that may prevent you from participating in the testing that has been outlined to you? ☐ ☐
If Yes, please provide details.
……………………………………………………………………………………………
……………………………………………………………………………………………
……………………………………………………………………………………………
………………

Your Recent Condition

Yes **No**

- Have you eaten in the last 2 hours? ☐ ☐
  If Yes, please provide details
  ……………………………………………………………………………………………
  ……………………………………………………………………………………………
  ………………

- Evaluate your diet over the last two days. **Poor** **Average** **Good** **Excellent**

Yes **No**

- Have you consumed alcohol in the last 24hr ☐ ☐

Yes **No**

- Have you had any kind of illness or infection in the last 2 weeks ☐ ☐

Yes **No**

- Have you exercised in the last 2 days? ☐ ☐

  If Yes, please describe below

……………………………………………………………………………………………
……………………………………………………………………………………………
……………………………………………………………………………………………
………………

Persons will not be permitted to take part in any experimental testing if they:-

- have a known history of medical disorders (i.e. hypertension, heart or lung disease)
- have a fever, suffer from fainting or dizzy spells
- are currently unable to train because of a joint or muscle injury
- have had any thermoregulatory disorder

- have gastrointestinal disorder
- have a history of infectious diseases (i.e. HIV or Hepatitis B)
- have, if pertinent to the study, a known history of rectal bleeding, anal fissures, haemorrhoids or any other similar rectal disorder.

My responses to the above questions are true to the best of my knowledge and I am assured that they will be held in the strictest confidence.

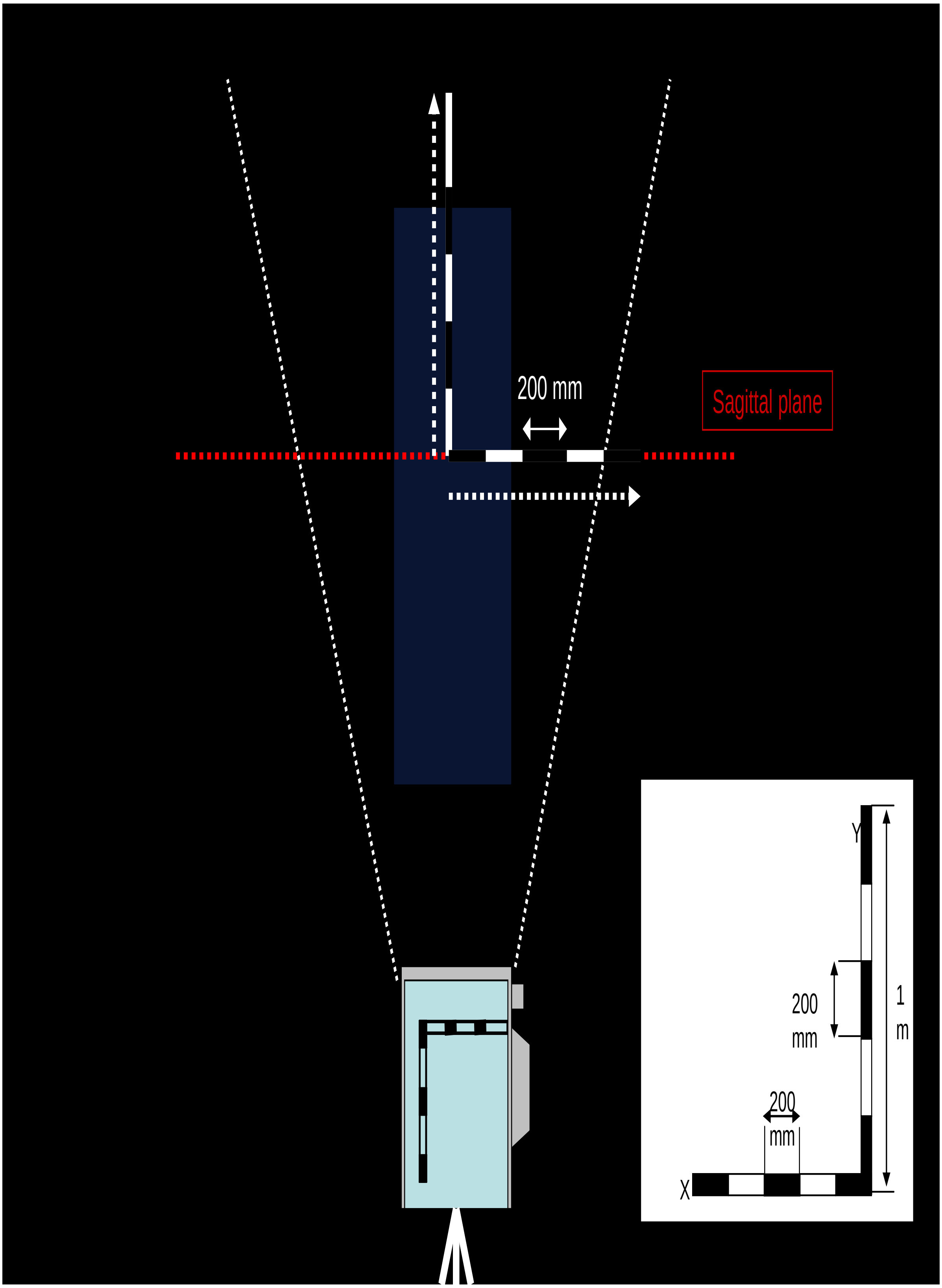
Name: (Participant)……………………………………………………….
Date:………………….

Signed (Participant): ………………………………………………….. ..

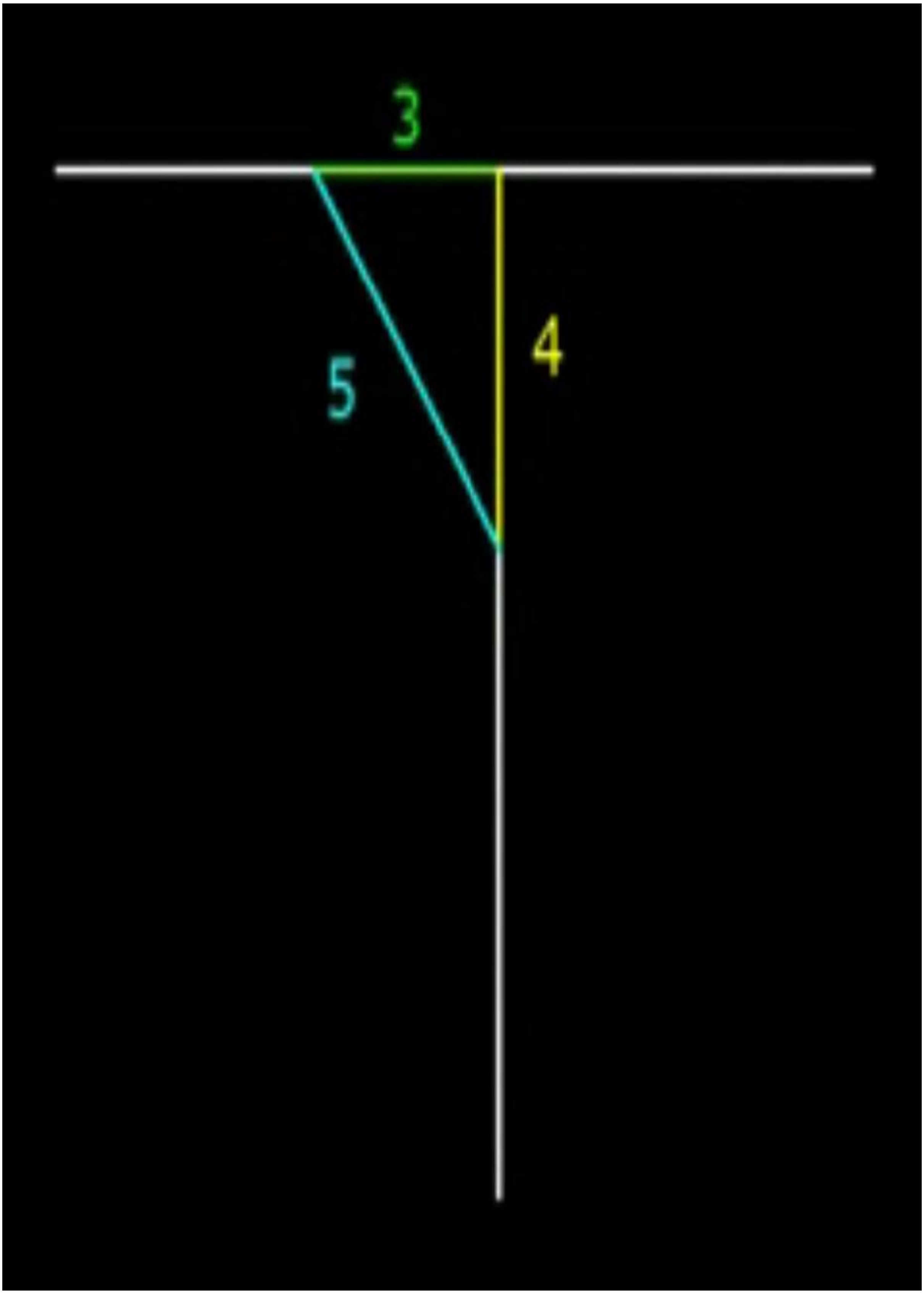
Name: (Lecturer/technician)…………………………………………….
Date:………………….

Signed (Lecturer/technician): …………………………………………...

Appendix 3.34 High speed camera calibration



Appendix 3.35 High speed camera positioning in relation to performance area



University of Chester
Faculty of Applied and Health Sciences
Research Ethics Committee

Appendix 4.31 (ethical approval study 2)

Robert William Connell

16th July 2009

Dear Robert,

Study title: A biomechanical analysis of the arm-swing countermovement during vertical jumping.
FREC reference: 316/09/RC/SES
Version number: 1

Thank you for sending the above-named application to the Faculty of Applied and Health Sciences Research Ethics Committee for review.

The application has been considered by the Faculty Research Ethics Committee.

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form and supporting documentation.

The favourable opinion is given provided that you comply with the conditions set out in the attached document. You are advised to study the conditions carefully.

The final list of documents reviewed and approved by the Committee is as follows:

With the Committee's best wishes for the success of this project.

Yours sincerely,

Mohammed Saeed
Chair, Faculty Research Ethics Committee

Enclosures Standard conditions of approval.
c.c. Supervisor FREC Representative

University of Chester

Appendix 5.31
Consent form

Title of project

An investigation into the effects of a 4-week upper-extremity plyometric intervention on vertical jump performance in club level male basketball players

Name of researcher

Mr. Robbie Connell

Please tick the box if you agree with the statement:

☐ I confirm that I have read and understood the participant information sheet for the above-named study, and have had the opportunity to ask the lead researcher any questions.

☐ I understand that my participation is voluntary, and that I am free to withdraw from participating in the study at any time, without giving any reason and without my rights being affected.

☐ I understand that my participation in this study will be video taped and I may collect a copy of my performance at the end of the test.

☐ I agree to participate in the above study

☐ I would/would not like to be informed of the results of this study (please delete as appropriate).

Name of participant ______________________

Date ______________________

Signature ______________________

Name of researcher ______________________

Date ______________________

Signature ______________________

Appendix 5.32 (pre-test health questionnaire study 3) Researcher name: Robbie Connell

DEPARTMENT OF SPORT AND EXERCISE SCIENCES UNIVERSITY OF CHESTER

PRE-TEST HEALTH QUESTIONNAIRE

(Please note that this information will be confidential)

Name.……………………………………………… DOB.…………… Age.…………....

Practical/Project Title.………………………………………………………………………………

Please answer these questions truthfully and completely. The purpose of this questionnaire is to ensure that you are fit and healthy enough to participate in this laboratory practical/research project.

Yes No

8. Have you in the past suffered from a serious illness or accident. ☐ ☐
   If Yes, please provide details.

   ……………………………………………………………………………………………………
   ……………………………………………………………………………………………………
   ……………...

Yes No

9. Have you consulted your doctor the last 6 months ☐ ☐
   If Yes, please provide details

………………………………………………………………………………………………
……………..………..…………………………………………………………………………
………………………………………………………

10. Do you suffer, or have you suffered from:

Yes No

Asthma ☐ ☐

Diabetes ☐ ☐

Bronchitis ☐ ☐

Epilepsy ☐ ☐

High blood pressure ☐ ☐

	Yes	No
11. Is there any history of heart disease in your family	☐	☐

	Yes	No
12. Are you suffering from any infectious skin diseases, sores, wounds, or blood infections i.e., Hepatitis B, HIV, etc.? If Yes, please provide brief details.	☐	☐

……………………………………………………………………………………………………
……………………………………………………………………………………………………
………………

	Yes	No
13. Are you currently taking any medication If Yes, please provide details.	☐	☐

……………………………………………………………………………………………………
……………………………………………………………………………………………………
……………………………………………………………………………………………………
………………………

	Yes	No
14. Are you suffering from a disease that inhibits the sweating process	☐	☐

	Yes	No
15. Is there anything to your knowledge that may prevent you from participating in the testing that has been outlined to you? If Yes, please provide details.	☐	☐

……………………………………………………………………………………………………
……………………………………………………………………………………………………
……………………………………………………………………………………………………
………………

Your Recent Condition

	Yes	No
• Have you eaten in the last 2 hours? If Yes, please provide details	☐	☐

……………………………………………………………………………………………………
……………………………………………………………………………………………………
………………

- Evaluate your diet over the last two days. **Poor** **Average** **Good** **Excellent**

	Yes	No
• Have you consumed alcohol in the last 24hr	☐	☐
• Have you had any kind of illness or infection in the last 2 weeks	☐	☐
• Have you exercised in the last 2 days?	☐	☐

If Yes, please describe below

……………………………………………………………………………………………………
……………………………………………………………………………………………………

……

Persons will not be permitted to take part in any experimental testing if they:-

- have a known history of medical disorders (i.e. hypertension, heart or lung disease)
- have a fever, suffer from fainting or dizzy spells
- are currently unable to train because of a joint or muscle injury
- have had any thermoregulatory disorder
- have gastrointestinal disorder
- have a history of infectious diseases (i.e. HIV or Hepatitis B)
- have, if pertinent to the study, a known history of rectal bleeding, anal fissures, haemorrhoids or any other similar rectal disorder.

My responses to the above questions are true to the best of my knowledge and I am assured that they will be held in the strictest confidence.

Name: (Participant)…………………………………………………….
Date:………………….

Signed (Participant): …………………………………………………..

Name: (Lecturer/technician)………………………………………….
Date:………………….

Signed (Lecturer/technician): …………………………………………...

Appendix 5.33 (ethical approval for study 3)

University of Chester

Faculty of Applied Sciences
Research Ethics Committee

Tel 01244 511740
Fax 01244 511302
frec@chester.ac.uk

Robert Connell

1st March 2012

Dear Robert,

Study title:	**An investigation into the effects of a 4-week upper-extremity plyometric intervention on vertical jump performance in club level male basketball players.**
FREC reference:	**533/11/RC/SES**
Version number:	**2**

Thank you for sending your application to the Faculty of Applied Sciences Research Ethics Committee for review.

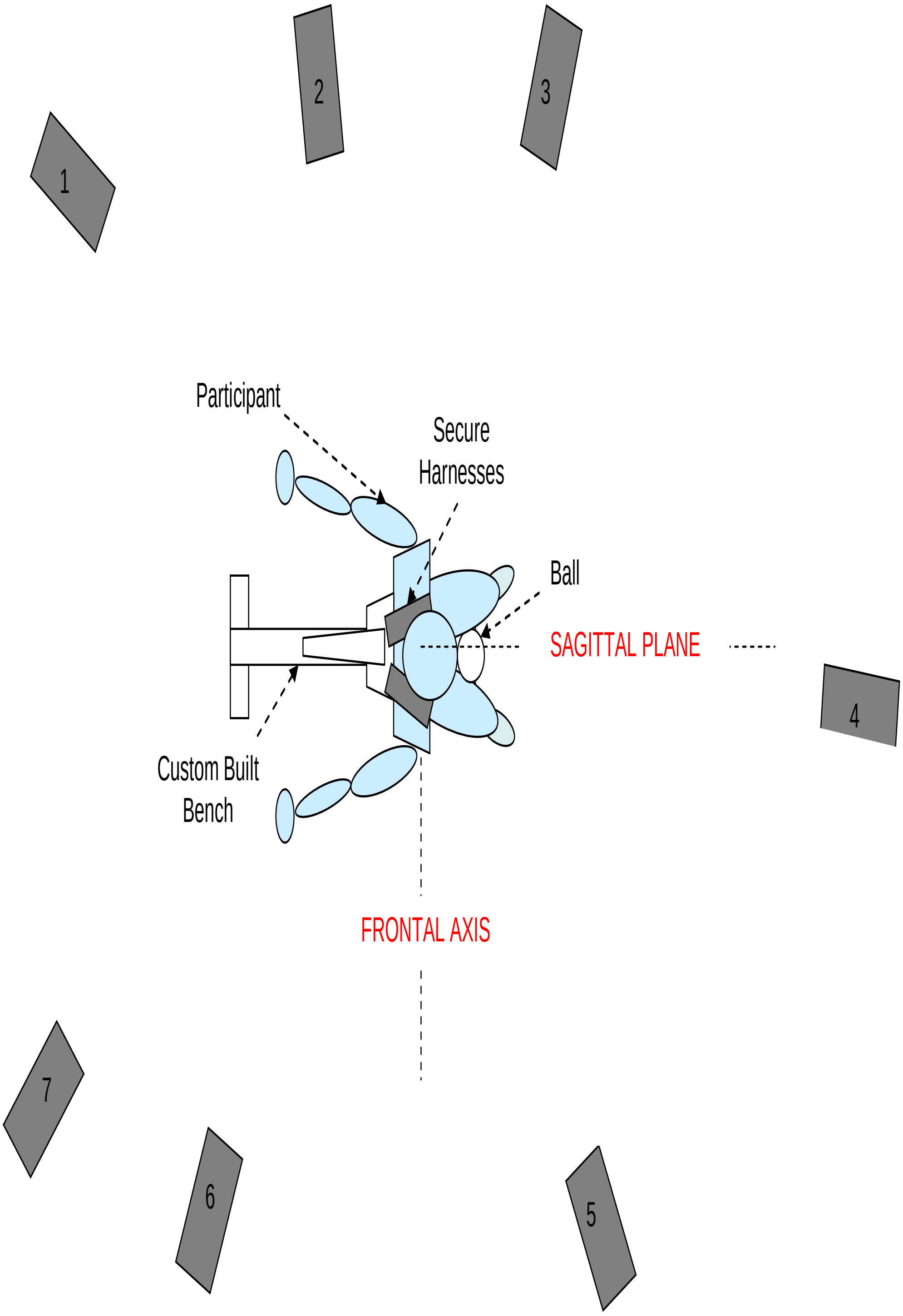
I am pleased to confirm ethical approval for the above research, provided that you comply with the conditions set out in the attached document, and adhere to the processes described in your application form and supporting documentation. However, the Committee recommends that the name of the Faculty shown on the Participant Information Sheet is amended to the Faculty of Applied Sciences.

Yours sincerely,

Cynthia V Burek

Prof. Cynthia Burek
Chair, Faculty Research Ethics Committee

Appendix 5.34 3D motion capture system and laboratory setup.



Appendix 5.35 Upper-extremity plyometric programme
* SBS: Short arm back-swing
** MBS: Large arm back-swing

	Week 1		**Week 2**		**Week 3**		**Week 4**	
	Sets	**Reps**	**Sets**	**Reps**	**Sets**	**Reps**	**Sets**	Reps
Exercise 1 **SBS rebound throws*** Left arm Right arm	1 1	10 10	2 2	10 10	2 2	15 15	3 3	15 15
Exercise 2 **MBS rebound throws**** Left arm Right arm	1 1	10 10	2 2	10 10	2 2	15 15	3 3	15 15
Exercise 3 **Weighted arm-swing burnouts** Left arm Right arm	1 1	10 10	2 2	10 10	2 2	15 15	3 3	15 15
Exercise 4 **Reverse overhead throws** Both arms	1	10	2	10	2	15	3	15
Exercise 5 **Medicine ball suicide drops** Both arms	1	10	2	10	2	15	3	15
Exercise 6 **Medicine ball floor slams** Left arm Right arm	1 1	10 10	2 2	10 10	2 2	15 15	3 3	15 15
Exercise 7 **Loaded theraband arm down-swings** (High load position) Both arms	1	10	2	10	2	15	3	15
Exercise 8 **Loaded theraband arm down-swings** (Low load position) Both arms	1	10	2	10	2	15	3	15

Appendix 5.41: Participants own choice during arm-swings

	Pre-test	
	Start	Back-swing
1	90	large
2	90	large
3	90	medium
4	90	large
5	45	large
6	90	large
7	90	large
8	45	large
9	90	large
10	90	medium
11	90	large
12	90	large
13	90	large
14	90	large
15	90	medium
16	90	medium
17	90	large
18	90	large
19	45	large
20	90	large
	85%	80%

RAW SPSS DATA