BIOMECHANICS OF TECHNIQUE SELECTION IN WOMEN'S ARTISTIC GYMNASTICS

by

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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ABSTRACT

BIOMECHANICS OF TECHNIQUE SELECTION IN WOMEN'S ARTISTIC GYMNASTICS

M.L. Manning, Cardiff Metropolitan University, 2014

Technique selection is fundamental to Women's Artistic Gymnastics with rapidly evolving difficulty and complexity; a result of changes in the scoring system and apparatus design. The aim of this research was to increase knowledge and understanding of the biomechanics underpinning female longswing techniques to determine effective technique selection. Five progressive themes addressed this aim; contemporary trend analysis, biomechanical conceptual approach, method validation, biomechanical musculoskeletal approach and biomechanical energetic approach. Elite competition provided the basis to the thesis with a strong ecologically valid trend analysis reporting the straddle Tkachev as the most frequently performed release skill preceded by three distinct longswing techniques; arch, straddle, pike. Quantifying each technique through a biomechanical conceptual approach enumerated differences observed and examined their influence on key release parameters. Significant differences ($p \leq 0.05$) were reported in the initiation and joint angular kinematics within the functional phases; however not for release parameters. Further examination into the joint kinetics and energetic demands of the gymnast were required to explain technique selection. Non-invasive methods of joint kinetic data collection are challenging within the elite competitive environment; therefore indirect methods were validated to provide confidence in the subsequent musculoskeletal approach. Inverse dynamic estimations were most sensitive to kinematic inputs with field versus lab comparisons highlighting systematic differences in joint moments (0.8%RMSD in consistency). Joint kinetics provided new knowledge of the underlying biomechanics of varying techniques, specifically greater shoulder joint moments and hip joint powers during the pike longswing. Examining gymnast energetic contribution to the total gymnast-high-bar energy system developed a novel effectiveness score highlighting the potential energy excess available to the arch (30%) and straddle (2%) techniques, indicating the potential to develop more complex versions of skills. This research provides coaches and scientists with specific physical preparation requirements for varying longswing techniques and insight into the need for customised technique selection.

PUBLICATIONS

Academic Journal Articles

Irwin, G., Exell, T., Manning, M. and Kerwin, D.G. (In Press). The evolution of the Tkachev on uneven bars. International Biomechanics.

Manning, M.L., Irwin, G., Gittoes M.J.R. and Kerwin, D.G. (2011). Influence of longswing technique on the kinematics and key release parameters of the straddle Tkachev on uneven bars. Sports Biomechanics, 10(3), 161-173.

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National Conference Abstracts

Manning, M., Irwin, G., Kerwin, D. and Gittoes, M. (2011). Predicting uneven bar forces during the female longswing. In M. Lauder (Ed.), Programme and Abstract book of the 26th British Association of Sports and Exercise Sciences Biomechanics Interest Group. University of Chichester, UK, 15.

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DEDICATION

To my devoted gymnastics coach, Chris Dodden

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NOMENCLATURE AND DEFINITIONS

Abbreviations used for terminology throughout the thesis

FIG   Fédération Internationale de Gymnastique

FP   Functional Phase

CM   Centre of Mass

2D   Two-Dimensional

3D   Three-Dimensional

DLT   Direct Linear Transformation

n   Number of samples

SD   Standard Deviation

RMSD   Root Mean Square Difference

%RMSD   Percentage Root Mean Square Difference

Max   Maximum

Min   Minimum

y   Horizontal direction

z   Vertical direction

i   Segment number

j   Joint number

m   Mass

h   Height

t   Time

v   Linear velocity

a   Linear acceleration

g   Acceleration due to gravity

F   Linear force acting on segment

IJF   Internal Joint Force

BW   Body Weight

BSIP   Body Segment Inertia Parameters

dis   Distance between the CM and distal end of the segment

pro   Distance between the CM and proximal end of the segment

ω   Angular velocity

α   Angular acceleration

I	Moment of inertia
wri	Wrist joint
shd	Shoulder joint
kne	Knee joint
ank	Ankle joint
IDA	Inverse Dynamics Analysis
Fb	Force at the bar
JM	Joint Moment
JP	Joint Power
JW	Joint Work
JMn	Normalised Joint Moment
JPn	Normalised Joint Power
JWn	Normalised Joint Work
SFP1	First Shoulder Functional Phase
SFP2	Second Shoulder Functional Phase
HFP1	First Hip Functional Phase
HFP2	Second Hip Functional Phase
E	Energy
En	Normalised Energy
ES	Effectiveness Score

CHAPTER ONE

INTRODUCTION

1.1 Overview of Research

Artistic gymnastics is one of the original sports included in the modern Olympics that epitomises physical prowess, technical accuracy and a high level of precision in movement. Over the last three decades artistic gymnastics has developed with spectacular advances in difficultly and diversity of skills being performed by men and women (Takei et al., 1992; Arkaev and Suchilin, 2004). More recently, changes in the rules including the scoring system and apparatus design have led to the incorporation of more complex skills (Fédération Internationalé de Gymnastique [FIG], 2013). The coaches' duty to provide safe, effective and efficient skill development programmes has become paramount in elite sports (Gould et al., 1990) and specifically artistic gymnastics (Readhead, 1997; Irwin et al., 2004).

The role of the coach in artistic gymnastics has developed alongside the continuous evolution of the sport through advances in skill difficulty and apparatus design (Irwin et al., 2005). Effective coaching practices enable appropriate technique to be developed; these techniques are imposed on the gymnast, by the coach, and are generally based on the technical requirements of the skill and physical characteristics of the gymnast. The desired technique is often taught to a group of gymnasts based on a model of performance embedded in the mindset of gymnastic coaches (Cote et al., 1995). These models of performance are often developed from coaching manuals, previous experience and interactive coaching clinics (Irwin et al., 2004). However, due to the difference in the characteristics of performers in terms of mass, height and strength for example, an individualised approach may be more effective.

The uneven bars are the evident piece of apparatus within Women's Artistic Gymnastics that have transformed gymnasts' routines due to changes in the apparatus and judging criteria. The complexity of current uneven bar routines exhibits the sport's development. On each apparatus there is a key skill, which is directly linked to the development of other more complex skills (Irwin and Kerwin, 2006; Hiley and Yeadon, 2007). On uneven bars this key skill is the longswing and is directly associated to the development of more advanced skills such as the Tkachev skill. Knowledge of the underlying mechanics that can then be transferred to increase coaches' understanding can help effective skill development

and selection of the most appropriate technique (Dowdell, 2010), particularly during the preparatory longswing.

Arkaev and Suchilin (2004) associated the laws of mechanics closely with the teaching laws of gymnastics and its importance in understanding the mechanisms underpinning technique. Sands et al. (2011) later supported the importance of biomechanics within artistic gymnastics highlighting that biomechanics is the science that can discover technique rather than simply identify the obvious. The changes in gymnast body position and movement patterns with respect to time and space encompasses essential biomechanical processes (Arkaev and Suchilin, 2004). Variations in longswing technique observed at an elite level are yet to be explained from a biological, physical and mechanical perspective.

The preparatory longswing is paramount in providing optimal release parameters for the successful execution of release and re-grasp skills and dismount skills (Cheetham, 1984; Arampatzis and Brüggemann, 1998; 1999; 2001; Yeadon and Hiley, 2000; Holvoet et al., 2002; Hiley and Yeadon, 2003, Hiley and Yeadon, 2005; Kerwin et al., 2007; Sheets and Hubbard, 2007; Kerwin and Irwin, 2010; Manning et al., 2011). A safe and effective trajectory away or over the bar is determined by the release parameters that include angle of release, horizontal velocity and vertical velocity of the gymnast's centre of mass (Fink, 1988; Brüggemann et al., 1994; Holvoet et al., 2002; Kerwin and Irwin, 2010). An investigation into the mechanics underpinning distinct longswing techniques and their effect on key release parameters has the potential to provide an increase in understanding of effective skill development by increasing a coach's technical knowledge and enhancing skill selection in the coaching process. Therefore, biomechanics can make coaching more effective hence reducing the time spent on 'trial and error' methods of coaching (Readhead, 1997; Sands et al., 2011).

Technique selection in Women's Artistic Gymnastics is primarily determined by the coach and can be influenced by coaching background and philosophy, gymnast size and physical characteristics. Gymnasts are training near their physiological limits and understanding intrinsic and extrinsic factors that influence technique selection may allow gymnasts and coaches to be more objective about the best techniques for their performers.

1.2 Background and Context

The longswing is a fundamental skill in artistic gymnastics consisting of the gymnast starting in a handstand position on top of the bar and then rotating backwards through 360°, with adjustments to shoulder and hip joints, to finish back in a handstand position. The longswing and its variations (accelerated [power and traditional] and general) are of paramount importance in Men's and Women's Artistic Gymnastics and research has focused on explaining the biomechanical processes involved (Arampatzis and Brüggemann, 1998; 1999; Hiley and Yeadon, 2005; Irwin and Kerwin, 2006; 2007). Research has identified that underpinning the success of this skill is a rapid hyper-extension to flexion at the hips and hyper-flexion to extension at the shoulders (Prassas et al., 1998; Hiley and Yeadon, 2003; Irwin and Kerwin, 2006). This has been termed the propulsion mechanism (Brüggemann et al., 1994) and the beat action (Gervais and Tally, 1993) by previous authors, but more recently the functional phase (Irwin and Kerwin, 2006). The functional phase provides the musculoskeletal work needed for the successful completion of the ascent phase and correct release parameters for dismounts and release and re-grasp skills (Arampatzis and Brüggemann, 1999; Irwin and Kerwin, 2006). In the general longswing 70% of musculoskeletal work was found to occur during the functional phase (Irwin and Kerwin, 2006).

In Women's Artistic Gymnastics, the female gymnasts have the added influence of the low bar and consequently change their body configuration during the descent of the longswing (for example through hip flexion, extension or abduction). Arampatzis and Brüggemann (1999) reported a loss of energy due to movement at the shoulder and hip joints being too passive when passing the low bar in women's gymnastics. Arampatzis and Brüggemann (1999) clarified that gymnasts should be in an extended position to increase the energy absorption when passing the low bar. Sheets and Hubbard (2007) established that by developing the movement at the hips from two dimensional to three dimensional (straddling of the legs), dismount performance (maximal number of dismount revolutions) was only decreased by 0.45% compared to 1.22% for shorter gymnasts and 2.00% compared to 3.59% for taller gymnasts. The timing of hip angle changes is also essential as a delayed maximum hip angle in females compared to males reduces the angular momentum generated (Hiley and Yeadon, 2005).

From observations of female elite level competition, there are varying longswing techniques passing the low bar on the uneven bars. However, there is no technique criterion to the best of the author's knowledge that constitutes the coach's technique

selection process. Therefore, the focus of this research was to identify the differences in technique and to investigate mechanical explanation for these differences through kinematic and kinetic analyses. By distinguishing an effective technique with the regard to the female longswing, this research has potential implications for developing understanding of the effectiveness of training and the coaching process in Women's Artistic Gymnastics to provide insight into potential skill development.

1.3 Research Aim and Purpose

1.3.1 Research Aim

The aim of this research was to increase knowledge and understanding of the biomechanics underpinning the techniques of the female longswing in artistic gymnastics for the determination of effective technique selection. By employing a thematic approach, five key themes were constructed in order to address the research aim; contemporary trend analysis, biomechanical conceptual approach, method validation, biomechanical musculoskeletal approach and biomechanical energetic approach.

1.3.2 Research Purpose

There is currently limited scientific justification for variation in technique in the female longswing. With the complexity of artistic gymnastics routines increasing and gymnasts training at their maximum, a scientific criteria applied to technique selection based on biomechanical understanding would allow for coaching and development to evolve at the same pace. An investigation into the underlying biomechanics of the distinctive longswing techniques and their effect on key release parameters and musculoskeletal demand was therefore warranted. The overall purpose of this thesis was to provide an increase in understanding of effective skill development by increasing a coach's technical knowledge and enhancing their skill selection in the coaching process.

1.4 Development of Research Themes

In order to address the overall research aim of this thesis, five themes were applied to encompass the identification, description and explanation of female longswing techniques. The formation of the thematic framework provided a scientific direction to the research conducted and furthermore the scope of the research chapters and individual research questions (Figure 1.1). A review of previous literature enabled an early establishment of

the distinct themes to emerge that conceptualised development and progression of the thesis.

Theme 1 was a **Contemporary Trend Analysis** that integrated high ecological validity within the research. Incorporating data from two International competitions provided coaches with real world data and trends providing meaningfulness and confidence to the findings and implications of this research. Collecting data from the field and conducting a trend analysis enabled the researcher to identify varying techniques and skill selection from a coach's view point, in parallel with coach education literature (British Gymnastics, 2007; FIG, 2013). In order to gain greater knowledge and understanding of the varying longswing techniques, quantification of the underlying movement patterns through biomechanical underpinnings were required, formulating Theme 2.

The **Biomechanical Conceptual Approach** of Theme 2 incorporated joint angular kinematic information to quantify the differences in longswing techniques. This approach provided coaches and scientists with a scientific description of the differences observed and the functional implications which are essential for the development of more advanced skills to allow gymnasts to reach their full potential (Igarashi, 1983; Sands et al., 2011). In order to determine the most effective technique for a particular skill, the female longswing, the influence of varying longswings on key release parameters were further examined. The release parameters of flight elements are paramount in defining the success and therefore effectiveness of their selection (Fink, 1988; Brüggemann et al., 1994; Holvoet et al., 2002; Kerwin and Irwin, 2010). Theme 2 provided coaches and scientists with knowledge of the biomechanics underpinning the principal movement patterns of varying longswing techniques and their influence on release parameters. However, the mechanical demands of these varying longswing techniques are unknown that can infer the physical demand placed on the gymnasts. Therefore the joint kinetic characteristics are required to account for and explain the observed differences. To ensure that ecological validity and confidence in implications continued to permeate throughout the research, a validation of methods utilised in the field were required, founding Theme 3.

Theme 3 was a **Method Validation** that was a prerequisite to measuring the mechanical loads that infer the physical demand of the varying longswing techniques to data being collected within the field. Within a competition environment, data are extremely difficult to collect through non-invasive methods and therefore the use of field based measures and the methods employed required investigation. Well documented research (Challis and Kerwin, 1996; Hatze, 2000; 2002; Robertson et al., 2014) has established that there are

errors associated with the inputs to an inverse dynamics analysis (IDA) and therefore an analysis of the errors connected to the indirect computation of joint kinetics for the female longswing is mandatory. With the applied scientist being faced with the challenging balance between control of the environment within lab based conditions and ecological validity (Elliott and Alderson, 2007), a further validation of indirect field measures to direct lab measures were required. The outcome of this theme would provide coaches and scientists with confidence in the subsequent kinetic and energetic findings and implications.

A **Biomechanical Musculoskeletal Approach** (Theme 4) extended the knowledge and understanding of varying longswing techniques through the examination of the mechanical demand placed on the gymnasts in an attempt to determine the most effective technique. Through the establishment of bar forces, joint moments, joint powers and joint work, explanations to differences in technique and an indication of the physical demand placed on the gymnast became apparent. Further biomechanical information also provided coaches with information for the physical preparation of gymnasts and the potential development of the skill, providing effective implications for training. The total joint work generated by the gymnast entails the energetic input from the gymnast to the gymnast-high bar system. Therefore, developing from Theme 4, a biomechanical energetic approach was completed to determine whether different energetic inputs were required from the gymnast deeming one longswing technique more effective, with the overall aim of understanding the mechanisms underpinning technique selection.

Theme 5 was a **Biomechanical Energetic Approach** that provided insight into the gymnast-high bar energy system and the gymnasts contribution, determining the varying movement patterns identified previously. Building on the concepts addressed by Arampatzis and Brüggemann (1999; 2011) and Irwin and Kerwin (2007), knowledge of the biomechanical energetics of varying longswing techniques permits the coach to tailor gymnast preparation and technique selection to be the most effective possible for the successful execution of a desired skill.

1.5 Organisation of Chapters

1.5.1 Chapter Two: Review of Literature

Chapter 2 consists of a review of key previous literature that has formulated the research surrounding artistic gymnastics, the coaching process and the identification of the

longswing as a fundamental skill in the successful completion of more complex skills. The methods of approach utilised by previous researchers both in and away from artistic gymnasts have also been addressed in an attempt to identify the most appropriate methods to maintain high ecological validity and scientific rigor. The review of literature provided the foundation to identifying the gaps within the current research and also established the thematic framework in order to address the overall thesis aim. Key results reported throughout the thesis fundamentally supported existing high bar and uneven bar literature or either extended or critiqued current concepts applied to technique selection of the female longswing.

1.5.2 Chapter Three: Trend Analysis of Release and Re-grasp Skills and the Preceding Longswing

Theme 1 of this research was the **contemporary trend analysis** focusing on the release and re-grasp skills and their preceding longswing. This study was performed to determine what skills elite gymnasts were performing following the backward longswing and to establish what the varying longswing techniques were. Chapter 2 highlighted the challenge that coaches and gymnasts have in developing with the advances of the sport in terms of difficulty and complexity; therefore identifying what is being performed is paramount. Data were collected from the qualification rounds of two International competitions (2000 Sydney Olympics and 2007 World Championships) and as well as the trends of the techniques and skills being performed, trends in gymnast height, mass and nationality were also investigated. Following the trend analysis that identified three distinct longswing techniques, the biomechanics underpinning these techniques were investigated to address the absence of scientific knowledge within the technique selection process.

1.5.3 Chapter Four: Kinematics and Angular Momentum of Longswing Techniques Preceding the Straddle Tkachev

Theme 2 was a **biomechanical conceptual approach** that was addressed through the application of joint angular kinematic and angular momentum analyses to determine the influence of longswing technique on successful release parameters. This study was key in determining whether particular longswing techniques permitted the gymnast to be in an advantageous position to perform the selected skill. Differences in longswing technique reported in Chapter 3 that are visible to the coach were further quantified and established significant differences in the joint angular kinematics. These differences however were not replicated in the release parameters and therefore more detailed kinetic analyses were required in order to address the overall research aim of explaining differences in technique

for effective technique selection. Utilising data from the field required validation and an assessment of the errors associated that were addressed in Chapter 5.

1.5.4 Chapter Five: Evaluation of Joint Kinetic Calculations during the Female Longswing Preceding the Straddle Tkachev

Theme 3 was **method validation** that was required in order to determine the errors associated with the field inputs to an inverse dynamics analysis (IDA) and to validate against inputs from a controlled environment, the lab. Chapter 5 was required before kinetic and energetic data could be calculated to provide confidence in the subsequent findings. A single subject methodological study was constructed to determine the direct effects of changing IDA input parameters as opposed to the influence of between subject variability. With knowledge of the errors associated with the validated proposed method of approach for the determination of joint kinetics and energetics, the physical demand of the varying longswing techniques were examined in Chapter 6.

1.5.5 Chapter Six: Kinetic and Energetic Analyses of Longswing Techniques Preceding the Straddle Tkachev

Theme 4 and 5 (**biomechanical musculoskeletal approach** and **biomechanical energetics approach**) were addressed through the kinetic and energetic analyses encompassed within Chapter 6. Acknowledgement of the errors associated with IDA applied to the female longswing and the influence of field based measures on the calculation of joint kinetics in Chapter 5 provided confidence and understanding to the joint kinetic implications reported. Joint kinetic analyses within the biomechanical musculoskeletal approach provided a measure of the varying mechanical demands on the gymnasts performing different longswing techniques. Energetic analyses examined the energetics contributed by the gymnast through muscular work to the gymnast-high bar energy system, in an attempt to explain the underlying differences in longswing techniques to determine the most effective technique selection process.

1.5.6 Chapter Seven: General Discussion

Chapter 7 incorporated a discussion of the key findings of the research with an appraisal of the thematic approach undertaken in addressing the overall thesis aim. Implications of the results are presented with the contributions to knowledge and underlying research philosophy detailed. Limitations of the research are discussed with recommendations for future investigations outlined.

Thesis Aim

Increase knowledge and understanding of the biomechanics underpinning varying techniques of the female longswing for the determination of effective technique selection

Theme 1
Contemporary Trend Analysis

Aim
To identify the longswing techniques elite gymnasts are performing and identify any trends in technique selection

Research Questions

1- What release and re-grasp skills are performed by elite female gymnasts during International competition?

2- What longswing techniques are used to precede the selected release and re-grasp elements?

3- What are the factors that influence the selection of longswing technique prior to release and re-grasp skills?

Theme 2
Biomechanical Conceptual Approach

Aim
To increase mechanical knowledge and understanding of longswing techniques and their influence on key release parameters

Research Questions

4- How do the kinematics of the longswing preceding the straddle Tkachev alter as a function of technique?

5- How do release parameters and angular momentum about the gymnast's CM and the bar change as a function of longswing technique?

6- How do segmental contributions to total body angular momentum differ in the three distinct longswing techniques?

Theme 3
Method Validation

Aim
To provide confidence in field based measures to maintain high ecological validity

Research Questions

7- What is the influence of changes in the input parameters on an inverse dynamics analysis and the consequent joint kinetics?

8- How do predicted bar forces, joint moments, joint powers and joint work calculated indirectly from field based measurements differ from those from lab based measurements?

9- What level of confidence can be had in mechanical findings that utilise indirect methods?

Theme 4
Biomechanical Musculoskeletal Approach

Aim
To explain and give reason to the mechanical differences observed in the joint kinematics for varying longswing techniques

Research Questions

10- How do joint kinetics vary during changes in preparatory longswing technique preceding the straddle Tkachev?

Theme 5
Biomechanical Energetics Approach

Aim
To examine energetic demands of varying longswing techniques to determine effective technique selection

Research Questions

11- How do energetic inputs from the gymnast vary for different longswing techniques and is one longswing technique considered more effective than another?

Chapter 1
Introduction

Chapter 2
Review of Literature

Study 1

Chapter 3
Trend Analysis of Release and Re-grasp Skills and the Preceding Longswing Technique

Study 2

Chapter 4
Kinematic and Angular Momentum Analyses of Longswing Techniques Preceding the Straddle Tkachev

Study 3

Chapter 5
Evaluation of Joint Kinetic Calculations during the Female Longswing Preceding the Straddle Tkachev

Study 4

Chapter 6
Kinetic and Energetic Analyses of Longswing Techniques Preceding the Straddle Tkachev

Chapter 7
General Discussion

Figure 1.1. A diagram to illustrate the thematic framework applied to the thesis and the corresponding aim and purpose with resulting research questions of each study to address the overall aim of the thesis.

CHAPTER TWO

REVIEW OF LITERATURE

2.1 Introduction

The review of literature within this chapter focuses on the technically demanding sport of Women's Artistic Gymnastics and the role of Sports Biomechanics within the coaching process. Coaching practices encompassing effective technique selection will allow for sustained development alongside this rapidly evolving sport, where knowledge and understanding of the technical requirement of skills is paramount. Firstly, an overview of the key characteristics of Women's Artistic Gymnastics is presented with the technical considerations for coaches highlighted. The coaching process and the importance of biomechanical understanding within technique selection are then addressed introducing the key skill of the female longswing as a direct link to the development of complexity on the uneven bars. Well documented, previous biomechanical literature on this fundamental skill is then critiqued together with the biomechanical evaluation of more advanced release and re-grasp skills that subsequently follow the preparatory longswing. An improved understanding of the biomechanical characteristics of the longswing underpins the overall aim of increasing knowledge for the identification of effective technique selection.

2.2 Women's Artistic Gymnastics

Women's Artistic Gymnastics is an Olympic sport that promotes individual flare and expertise. Takei et al. (1992) described artistic gymnastics as a sport with remarkable advances and rapid development and training. In order to keep up with the increasing difficulty of the sport, original and complex performances are paramount and through elite coaching, delivered. Over the last decade, changes in the rules and design of apparatus by the International Governing Body, Fédération Internationalé de Gymnastique (FIG), has encouraged the incorporation of more complex skills and increased the possibility of performing them safely and successfully (Irwin et al., 2005). Paul (2010) highlighted the shift in focus from an appreciation of artistry to gymnast athleticism with the increase in complexity encouraged in the most recent advances by the FIG. Of the four pieces in Women's Artistic Gymnastics (vault, uneven bars, beam and floor), the uneven bars solely demonstrates an unbroken routine of elements where pauses or an 'intermediate' swing is

penalised with the connection value discounted (FIG, 2013). This provides the unique opportunity for continuous analysis of both preparatory and complex elements.

2.2.1 The Uneven Bars

The uneven bars, developed from the male parallel bars, consist of a high bar at 2.50 m and a low bar at 1.70 m, separated by an adjustable diagonal distance of $1.30 - 1.80$ m (FIG, 2013). Competitive routines on the uneven bars comprise circling skills, both forwards and backwards, and prominent flights elements interchanging between the two bars and over the high bar to re-grasp. The most recent change in the technical requirements of the uneven bars is the change in maximum bar spacing. Although the distance has always been self-selected by the gymnast, up until the end of the 20th century the bar spacing was restricted to go to a limited distance of 1.60 m. The Sydney 2000 Olympic Games was the first major International competition to comply with the separation distance of 1.30 m and 1.80 m (FIG, 2013). This change has influenced female gymnast's performance by introducing new versions of skills such as the straddle Tkachev being performed in the opposite direction to the traditional way (Kerwin et al., 2007).

Gymnasts have overcome the common problem of passing the low bar by changing their body configuration. Changes in the bar spacing has permitted the gymnast to pass the low bar in a less constrained, straight body position (Sands et al., 2003). Gymnasts have also adopted movement patterns to the other extreme where a higher frequency in the number of stooped and stalder skills have been observed. For example, the stooped Tkachev was only performed by one gymnast in the Sydney 2000 Olympic Games compared to eight in the 2007 World Championships in Stuttgart.

Frequently, coaches are seen changing the tension of the cables which allows the gymnast to effectively use the stiffness of the uneven bars to their advantage (Sands, 2000). This highlights how the properties of the bars combined with the developments of scientific knowledge and understanding in the field of gymnastics can aid in the execution of successful performance.

The uneven bars have undergone the biggest transformation in routine composition and have been influenced by the apparatus configuration and changes in the judging criteria; namely the Code of Points. The Code of Points, although it isn't a teaching or training document, has a large impact on what is taught to gymnasts (Sands, 2000).

2.2.2 Code of Points

The Code of Points is a set of rules that dictates the movement patterns required on all four pieces in Women's Artistic Gymnastics. The FIG aims to maintain consistency in the rules, requirements and element evaluations of Women's Artistic Gymnastics through the code. It has been designed to encourage variety, creativity and mastered difficulties, with a scoring system that insures the inclusion of the most difficult, complex elements (FIG, 2013). Gymnastic skills are based on a scoring continuum within the code with elements with the lowest difficulty rating classed as an 'A' skill through to the complex skills with the highest difficulty categorised as a 'G' value (Figure 2.2). The code is continuously reviewed and updated every four years to keep up with the growing complexity of the sport and the addition of new, intricate skills (FIG, 2013). As well as the introduction of original elements, recent developments of the rules cause changes in the code.
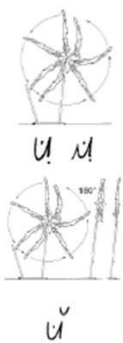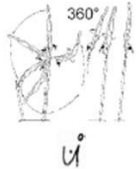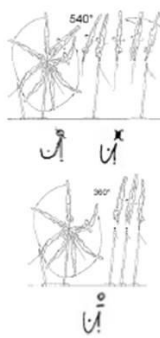
Figure 2.1. Element difficulty continuum outlined in the Code of Points (Adapted from FIG, 2013).

The change in the Code of Points in 2006 saw the introduction of a score composed of the product of a difficulty score and an execution score, to replace one score being marked out of a starting value of 10.00. This enabled gymnasts and coaches to compose routines of high complexity, improving their difficulty score and having a separate mark for execution. Ferreirinha et al. (2011) reported significant increases in difficulty in uneven bar routines between the Olympic cycle prior to the change in the code of points (2001-2004) and the Olympiad including the change in scoring system (2005-2008). This highlights the vast evolution of uneven bar routines that gymnasts are now executing under the new flexibility of the code of points. Particular advances in difficulty were reported in flight element

difficulty, high bar element difficulty, number of connections and the number of elements ranked D-F (Ferreirinha et al., 2011).

The magnitude of the increase in bar spacing in 2000 from 1.60 m to 1.80 m provided gymnasts with the potential to swing more freely, reducing the characteristic hip flexion introduced to pass the low bar (Prasses et al., 2006). The new styles of swinging are more reminiscent of male high bar (Kerwin and Irwin, 2010) and as such have allowed female gymnasts to explore new skills using different techniques.

Ferreirinha et al. (2010) highlighted the importance of body posture and position in order to increase the difficulty value of elements in terms of body configuration and/or rotation. One key factor therefore that influences technique selection that is paramount for the gymnast to optimise their performance is gymnast body shape and size (morphology).

2.2.3 Gymnast Physical Characteristics

Anthropometric characteristics of female artistic gymnasts have had considerable reviews, from both an injury (Sands, 2000) and performance perspective (Sherman et al., 1996; Claessens et al., 1999; Ackland et al., 2003; Ackland et al., 2005). The common coaching view that smaller gymnasts with high strength to mass ratio are more adequate at handling their own mass during complex rotational gymnastics skills (Vercruyssen, 1984; Ackland et al., 2003; Ackland et al., 2005) highlights the potential importance of the influence of anthropometric characteristics on performance (Claessens et al., 1999). However, before the influence of morphology is even considered, the nature of artistic performance causes an immediate scrutiny of gymnast body size and mass (Cintado, 2007). In the past, smaller, slimmer gymnasts have been perceived to have the edge and perform more aesthetically and successfully. However, gymnasts over the last decade that are taller as well as linear, such as the Russian gymnast Svetlana Khorkina, have successfully worked the Code of Points to their advantage and have had considerable success (Ackland et al., 2003). Throughout the maturity of women's gymnastics and her career as an International gymnast, Khorkina successfully adapted and performed eight new 'signature' skills into the Code of Points. Nadia Comaneci, the 1976 Montreal Olympic Champion stood at 1.47 m and weighed in at 39.9 kg, compared to Khorkina's 1.64 m stature and 45.9 kg mass.

The collection of data on gymnast physique has been identified as a research tool to facilitate an understanding of the link between performance and morphological characteristics (Kerr et al., 1995). Based on the assumption that performance is related to body morphology in many sports, Landers et al. (2000) investigated the importance of the

physical characteristics significantly related to the performance of elite-level triathletes. Four key morphological factors emerging that had the greatest influence on performance were robustness (strength and stability), adiposity, segmental lengths and skeletal mass. Segmental length characteristics in particular illustrated importance in the outcome of successful swimming performance (Landers et al., 2000).

Dellanini et al. (2003), using a musculoskeletal modelling and simulation approach, found linear relationships to predict the effect of percentage increases of bone cortical area on static and dynamic properties of limbs. An 80% increase in cortical area increased shank and thigh moments of inertia by 6.9% and 1.5% respectively; thus having an effect on rotational performance. They suggested that the effects of cortical area on internal work during maximum effort would be predicted higher than in their current study, highlighting an added influence of skeletal mass and size on performance.

Mass, together with other inertial characteristics, is essential in determining the dynamic characteristics of gymnastic movements (Arkaev and Suchilin, 2004). The inertial characteristics of the performer are key factors influencing performance. These biomechanical parameters determine the musculoskeletal demand placed on the performer (Kerwin and Irwin, 2010) and hence determine the choice of technique. The physical characteristic of the gymnast will provide the coach with indicators that they use to influence technique selection.

Sheets and Hubbard (2008) identified that a traditional coaching practice in Women's Artistic Gymnastics is for a new skill to be taught to a group of gymnasts once successfully performed by trial and error with little understanding about the influence of body size and strength. The author's approach of forward dynamic modelling required a simulation model consisting of a single segment torso and shoulder compliance approximated utilising a spring and damper; both factors were insufficient to accurately determine subject specific longswing technique. The above study highlights the difficulty in customising coaching and skill development to individual gymnasts.

Combining gymnast physical characteristics with other influences in determining technique, for example apparatus design and construction, coaching philosophy and following skill, the coach has to determine the most appropriate coaching pathway to take. Establishing the most effective and efficient coaching process is key to skill development and successful performance.

2.3 Coaching

2.3.1 Coaching Process

The coaching process, defined by Lyle (2000), is the delivery of a cognitive preparation and competition programme in order to achieve purposeful improvements in competition performance. With sports such as gymnastics continuously expanding in terms of difficulty and complexity, effective and efficient pathways for skill development need to be discovered (Irwin et al., 2005) to keep up with the sport. Irwin et al. (2004) investigated the origins of elite coaching knowledge and highlighted the need to examine how coaches utilise this information in order to develop gymnastic skills. The coaching process itself is a complex system with a multitude of factors influencing the pathway the coach implements that they see best for their athlete.

Female gymnasts aiming for an elite level career in gymnastics are faced with large volumes of intense training from an early age. Young gymnasts have their coach as an authority figure from the beginning (Sey, 2008) promoting discipline and making paramount decisions in the training environment. The coach holds a tremendous responsibility in coaching practice, coaching pathways, technique selection and skill development.

In a novice gymnastics environment it is common for a desired skill to be taught to a whole group with trial and error and experimental learning occurring. Until the skill has been performed successfully, the progression or coaching isn't deemed efficient. Effective training together with technique selection from coaches can reduce the time spent on 'trial and error' methods (Readhead, 1997; Sands et al., 2011). Dowdell (2010) emphasised the importance of knowledge application in the understanding of human performance within effective gymnastics coaching.

Skill progressions within artistic gymnastics are fundamental in the learning and development of more complex skills (Irwin et al., 2005). Within the coaching process Irwin et al. (2005) identified that establishing a conceptual mindset of a skill permitted the coach to form essential technical understanding to apply to skill development. Coach observation is thought to be the most frequent tool within gymnasts coaching and provides an understanding of the broad aspects within the movements observed (Dowdell, 2010), however Igarashi (1983) highlighted that advanced skills within artistic gymnastics require scientific knowledge to aid coaches in assisting gymnasts to reach their full potential. In Women's Artistic Gymnastics, it is the coach that has primary control over gymnast

training and development, and has a key responsibility in selecting the safest and most effective technique for the gymnast.

2.3.2 Technique Selection

Lees (2002) provided a general definition of technique from a biomechanical perspective as the relative position and orientation of body segments as they change during the effective performance of a sports task. For a performed skill, Lees (2002) suggested that technique can be categorised into different styles, general or specific; both of which would influence the selection process. In addition to this, technique selection can be dictated by the technical requirements of a skill and the physical characteristics of the performer. Specific to the sports of artistic gymnastics is the fact that the performance, and hence outcome of competition, is determined by the technique and not another secondary outcome such as distance, time or goals scored. The FIG code of points comprises each individual element in Women's Artistic Gymnastics. Although not reported, a large number of skills can be performed with slight modifications to the movement patterns incorporated providing different techniques. Selecting the most appropriate, efficient and safe technique is an important task of the coach.

Changes in technique are essential in order to keep up with the continuous development of gymnastics, but it is also important that these changes do not take valuable time and hinder successful performance (Sanders, 1995). Kerwin et al. (1993) examined the advantages of a novel hand placement in men's vaulting that emerged from a rule change removing the restrictions of hand placement. The above authors investigated differences in performance variables (pre and post flight linear and angular velocity) between two distinct vaulting techniques; both hands placed on the top of the vault or one on the vertical front surface with the other on the top. Significant differences occurred in the post flight horizontal velocity with the traditional technique (both hands on the top) concluded as the preferred technique. Further differences were in the approach linear velocity that suggests gymnasts performing the new technique may require an increased velocity in the run up to the vault. Theoretical expectancies such as increased rotation due to the 'blocking' of increased horizontal force were not evidenced, however Kerwin et al. (1993) suggested this could have been an outcome of the group design employed. Elite competition data were utilised from the 1991 World Student Games with the top two performances executing the new technique with the remainder of the gymnasts placing their hands on the front vertical at the bottom of the group.

Hiley et al. (2009) identified that there were two different techniques used to perform the felge on the parallel bars. Varying mechanical demands were required of the gymnasts performing the stooped technique compared to the more traditional clear circle technique. These authors suggested that the biomechanical information on observed differences in technique may be beneficial for coaches to utilise within the coaching process with a particular technique being selected at different stages of learning. The stoop technique required greater strength inputs from the gymnast and therefore more suitable to senior male gymnasts, with the additional potential of skill development complexity (Hiley et al., 2009).

With application to the high bar, Naundorf et al. (2010) similarly identified two varying techniques to perform the same skill; high and low starting techniques in the stoop circle on high bar. These authors investigated which technique enabled better development for more advanced skills and the underlying biomechanical requirements of these varying techniques. By concluding that the high technique placed a greater mechanical demand on the gymnast in terms of hip and shoulder joint kinematics, technique selection in the training for this particular skill was suggested to consider the difference in strength training required in an attempt to make training more specific to the desired final skill (Irwin et al., 2005; Naundorf et al., 2010).

As well as investigation into the influence of varying techniques on performance outcomes and proposed technique specific physical preparation, selection from an injury perspective has also been examined. Farana et al. (2013) explored the influence of hand placement in different vaulting techniques in female gymnastics on impact forces and joint moments at the elbow. With the application of a biomechanical approach these authors were able to determine a technique that was less prone to injury due to reduced vertical and anterior posterior ground reaction forces, enhancing the technique selection process.

With focus on the uneven bars in Women's Artistic Gymnastics, Kerwin and Irwin (2010) examined differences in longswing technique preceding the straddle Tkachev determined by the direction of the preparatory longswing. Implications for training specificity and skill development were reported with the inward, newer technique executing a higher release trajectory and significantly different shoulder moment contributions. The longswing on the uneven bars is key to the development of uneven bar routines, and changes in the body configuration in the initial phase of the longswing provide varying techniques. These changes in the longswing do not change the difficulty of the element and therefore their

difficulty value within the code of points (FIG, 2013), but may provide mechanical benefits to enhance performance (Sheets and Hubbard, 2007).

Ultimate mastery of the uneven bars is dictated by the technical accuracy of the longswing, and a high level of mechanical understanding of the longswing will provide coaches with the scientific knowledge to aid in the selection of the most appropriate technique (Readhead, 1997; Sands et al., 2011). Prassas et al. (2006) identified key areas that the application of biomechanics can assist with and specifically to the sport of gymnastics these included the understanding of existing techniques, new skill development, an increase in safety and the interaction between the gymnast and equipment.

2.4 Biomechanics of the Longswing

The backward longswing (Figure 2.2) has become a tool on the uneven bars to provide optimal performance parameters for subsequent skills; rather than a scoring element in itself (Prassas et al., 2006). Ferreirinha et al. (2010) reported a significant decrease in the number of longswings preceding the preparatory longswing prior to flight elements post the increase in bar spacing in 2000. With the added influence of the low bar, the female gymnasts have a number of options in passing the bar effectively and completing circling skills successfully. Coaches are faced with factors such as gymnast morphology and technical requirements of the following skill when considering which technique to employ.

Figure 2.2. The backward longswing on uneven bars (Manning et al., 2009).

By providing mechanical analyses of these techniques and the technical requirements of subsequent skills, coaches can gain greater knowledge and understanding of longswing techniques and make key technique selections (Kopp and Reid, 1980).

The backward longswing has been a heavily researched skill in the sport of gymnastics and Fink (1985) reported that the developments in equipment and the skill itself 45 years prior to their work meant there were still gaps in the research. Over the last decade of the 20th century and the beginning of the 21st century, consistent and further evolution of this particular apparatus highlights that there is still scope for further research into this fundamental skill to maintain safe and effective training within Women's Artistic Gymnastics.

As well as the identification of the mechanics associated with the backward longswing (Borms et al., 1976; Boone, 1977; Kerwin, 1999; Yeadon and Hiley, 2000), research into the backward longswing has addressed two key areas; the facilitation of successful release and re-grasp and dismount skills (Cheetham, 1984; Arampatzis and Brüggemann, 1998; 1999; 2001; Yeadon and Hiley, 2000; Holvoet et al., 2002; Hiley and Yeadon, 2003; 2005; Kerwin et al., 2007; Sheets and Hubbard, 2007; Kerwin and Irwin, 2010; Manning et al., 2011) and the association with skill development (Irwin and Kerwin, 2005; 2006; 2007).

2.4.1 Kinematics

Early research of the backward longswing highlighted the importance of changing the gymnasts' centre of mass location in order to facilitate the successful descent and ascent in longswing execution (Borms et al., 1976; Boone, 1977; Boykin and Breskman, 1980). The specific adjustments to the shoulder and hip joints as the gymnast rotated around the bar were further acknowledged in the success of basic longswing technique (Yeadon and Hiley, 2000) with Borms et al. (1976) focusing on the importance of hip extension during the descent phase of the longswing followed by hip flexion during the ascent. Prassas et al. (1998) suggested that the hip extension illustrated during the downswing of the skill permitted a greater hip flexion characteristic during the ascending phase of the longswing.

Research has identified that the rapid hyper-extension to flexion at the hips and hyper-flexion to extension at the shoulders underpins the success of backward longswing (Prassas et al., 1998; Hiley and Yeadon, 2003; Irwin and Kerwin, 2006; 2007) (Figure 2.3). This has been termed the functional phase (Irwin and Kerwin, 2006) and has been reported to provide the musculoskeletal work needed for the successful completion of the ascent phase

and correct release parameters for following dismount and release and re-grasp skills (Arampatzis and Brüggemann, 1999; Irwin and Kerwin, 2006).
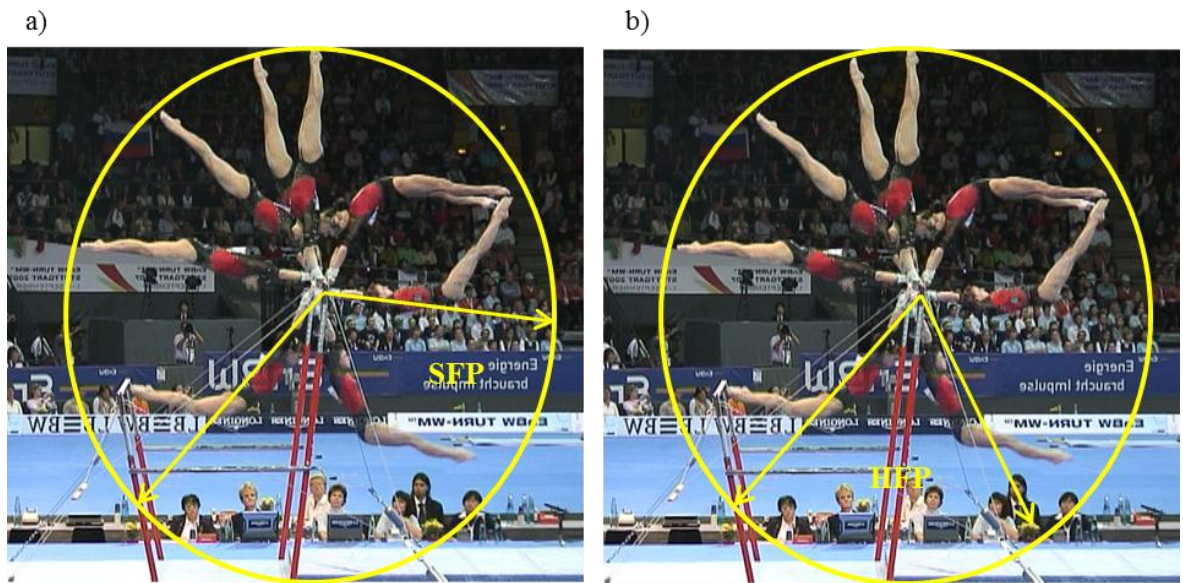
Figure 2.3. The initiation and conclusion of the a) shoulder (SFP) and b) hip (HFP) functional phase in the backward long swing (Adapted from Manning et al., 2011).

Cheetham (1984) investigated the differences in angular kinematics between three different longswing techniques; regular, dismount and wind up. The author identified the importance of the location of hip extension, termed the 'beat action', for the accurate timing of maximum angular velocity. Cheetham (1984) identified two key peaks of angular velocity; at the end of the descent phase due to gravity and at the end of the ascent phase or prior to release due to the gymnast work and the 'beat action'. For one of the varying techniques, the dismount longswing, angular velocity was required to be greater than the first peak to obtain successful release parameters.

Hiley and Yeadon (2003) identified two varying longswing techniques for male gymnasts executing the preparatory longswing preceding a double layout somersault dismount; the traditional and scooped longswing technique. The key differences between the two techniques were the locations of shoulder and hip functional phases. The scooped technique illustrated a far later 'closing phase' (shoulder extension and hip flexion) once the gymnast passed beneath the high bar and the opening phase (shoulder flexion and hip extension) occurred significantly later once the gymnast had passed the highest point (Hiley and Yeadon, 2003). Together with the more frequent execution of the scooped technique by elite gymnasts, the difference in joint angular kinematics were hypothesised by Hiley and Yeadon (2003) to facilitate more angular momentum at release. However,

these authors rejected their hypothesis as the traditional technique produced 10% more angular momentum than the scooped technique and therefore the selection criteria for the technique adopted was suggested to lie elsewhere. It is important to highlight that although there were differences in the release parameters of the two varying longswing techniques, both produced sufficient angular momentum to complete the desired dismount successfully and therefore were effective longswing techniques.

2.4.2 Kinetics

The successful execution of the longswing is determined by the gymnast generating sufficient angular momentum throughout the longswing in order to overcome the effects of friction and air resistance on the ascending phase of the swing (Yeadon and Hiley, 2000). When manipulating their body shape through adjustment of the hip and shoulder joints, the gymnast aims to optimise angular momentum and the transfer of energy into the bar as well as clear the low bar in order to complete the following complex skills (Hiley and Yeadon, 2005). Providing sufficient angular momentum for release and dismount skills is a key function of the backward longswing, with another being to link circling skills (Hiley and Yeadon, 2003). Maintaining an extended body position during the descent phase increases the moment of the performers weight around the high bar and thus increases the gymnast's angular momentum about the bar (Witten et al., 1996; Prassas et al., 2006; Williams et al., 2012). During the ascent phase the movement patterns at the shoulder and hip joints decrease the moment of inertia by bringing the gymnasts centre of mass closer to the bar and therefore maintaining sufficient angular momentum.

Knowledge of the forces applied to the high bar by the male and female gymnast is important in the examination of longswing technique as well as investigating injury mechanisms (Kerwin and Irwin, 2006). Early work of Ishii and Komatsu (1987) and Kopp and Reid (1980) identified that maximum bar forces during the longswing were approximately 3.5 times the gymnast's body weight and occurred after the gymnast had passed directly beneath the high bar. The above studies focused on the male longswing and when Witten et al. (1996) applied a similar investigation to the female longswing, a slightly lower maximum bar force (3.1 BW) before the gymnast passed beneath the high bar was reported. Witten et al. (1996) inferred that the difference in maximum bar force location may have been due to the change in body configuration in order to pass the low bar. A characteristic of the female longswing not identified in the male version was a second pull on the high bar as the gymnast entered the final quadrant of the longswing (Witten et al., 1996). These authors surmised that the bar recoil, as a consequence of the

second force applied by the female gymnast, assisted the gymnast in completing the longswing; highlighting an additional interaction between the gymnast and bar.

Yeadon and Hiley (2000) identified that the biomechanics underpinning longswing technique consisted of the joint moments at the shoulders and hips that determined the location of the shoulder and hip functional phases. As the gymnast descends on the downswing, joint moments to close the hip joint are required in order to overcome the passive kinetics opening the hip joint (Yeadon and Hiley, 2000) and to maintain optimal full body extension. Witten et al. (1996) further highlighted the importance of the shoulder and hip kinetics as a functional characteristic of the backwards longswing. Irwin and Kerwin (2005) supported this term defining the hyper-flexion to extension at the shoulder and hyper-extension to flexion at the hips as the 'functional' phase due to 70% of the gymnast work occurring during this period.

Irwin and Kerwin (2007) later established the musculoskeletal demands of the chalked bar longswing in Men's Artistic Gymnastics in order to compare against eight commonly used progressions. These authors reported a dominant contribution of the shoulder joint with large shoulder moments and powers during the first half of the ascent phase and a distinctive pattern in hip joint moments. Concurring with Okamoto et al. (1987b) and Arampatzis and Brüggemann (1999), Irwin and Kerwin (2007) reported negative hip joint moments prior to the gymnast passing below the high bar and positive hip joint moments during the first phase of the upswing.

Addressing the importance of specificity in skill progressions to the target final skill, Irwin and Kerwin (2007) reported differences in similarity when examining joint kinematics and joint kinetics of the longswing. These authors highlighted the importance of identifying whether progressions should adopt similar movement patterns or similar physical demands and therefore musculoskeletal stresses on the performer as the final skill. Determining the joint kinetics through the application of biomechanical musculoskeletal analyses can maximise technique selection and the safety of gymnasts (Bradshaw and Hume, 2012).

From an injury perspective upper extremity injuries at the arm and wrist have been reported to account for 12% of the most frequently injured sites in female gymnastics (Bradshaw and Hume, 2012), with wrist injuries a result of the nature of hand support skills as well as repetitive load bearing rotational manoeuvres with high hand grip strength (Amaral et al., 2011). The calculation of biological loading limits through joint kinetic analyses is therefore required to determine the musculoskeletal demand placed on the gymnast and to provide insight into the effectiveness of injury prevention measures

(Bradshaw and Hume, 2012). The repetitive nature of the female longswing in both a training and competition environment and the physical preparation techniques selected by the coach highlights the possible extrinsic risk factors for gymnastics' injuries reported by Bradshaw and Hume (2012).

2.4.3 Energetics

Bauer (1983) identified that within the backward longswing, an increase in mechanical energy was established by varying the pendulum length or changing the gymnast's centre of mass location. The above author however noted that missing from the theoretical model of a pendulum of varying length was the interaction of the shoulder and hip joints providing flexion and extension. Energy is lost during the longswing due to friction at the hands and air resistance (Sheets and Hubbard, 2009), but although these losses are relatively small (Hiley and Yeadon, 2001), muscular work is required from the gymnast in order to complete the longswing successfully (Okamoto et al., 1987a). Okamoto et al. (1987b) reported that the shoulder and hip joint contributed significantly to the successful completion of the longswing (48% and 46% respectively) and occurred in the first half of the ascent phase.

During the downswing, the joint moments previously reported that cause flexion to overcome the passive kinetics of opening the hip joint (Hiley and Yeadon, 2000) result in a concentric action that increases gymnast energy into the gymnast-high bar energy system (Hiley and Yeadon, 2001). Arampatzis and Brüggemann (1998; 1999; 2001) examined the gymnast-energy high bar system with specific interest in the interaction of the gymnast with the equipment. The elastic characteristic of the high bar allows for the storage and recovery of energy if the correct longswing technique is used (Arampatzis and Brüggemann, 1998; 1999; 2001; Prassas et al., 2006). The muscle work during the downswing therefore cannot be regarded as insufficient or as just a means to pass the low bar in the female longswing due to the transfer of energy into the bar (Arampatzis and Brüggemann, 1998). Arampatzis and Brüggemann (1998) established a criterion score for the utilisation of the elastic properties of the bar by calculating the difference between the decrease in gymnast energy and the increase in bar energy. Due to these authors applying this to the longswing preceding release and re-grasp skills, the criterion is further detailed in 2.5.3.

The importance of the kinematic and kinetic characteristics of the preceding longswing to match that of the linear and angular requirements of the following release and re-grasp skill was highlighted by Prassas et al. (2006).

2.5 Biomechanics of Release and Re-Grasp Skills

Release and re-grasp skills form part of the composition requirements in the code of points on uneven bars. The FIG (2013) states that a minimum of two flight elements are required and therefore to increase the difficulty value of an uneven bar routine release and re-grasp skills have to be incorporated (FIG, 2013). Gervais and Tally (1993) reported the importance of skill combinations on the men's high bar, which is also evident on the women's uneven bars where complex preliminary and following skills are more common.

Successful execution of these skills is primarily judged on the flight phase of the skill which has a small margin for error in comparison to other high bar skills (Gervais and Tally, 1993). Coaching the gymnasts to obtain the correct trajectory in their flight phase can be enhanced by technical knowledge at the release point. It is at this point that the aid of biomechanical knowledge plays a major role. The success of release and re-grasp elements in artistic gymnastics is dictated by three key factors at the point of release; angle of release, horizontal velocity and vertical velocity of the centre of mass. The trajectory is determined by the three key release parameters with their relative contribution determining the shape of the parabola (Fink, 1988; Brüggemann et al., 1994; Holvoet et al., 2002; Kerwin and Irwin, 2010).

Holvoet et al. (2002) reported the Tkachev as one of the most frequently performed release and re-grasp elements within artistic gymnasts and consequently has been the focus of a large cohort of previous literature (Fink, 1988; Ĉuk et al., 2009; Hiley et al., 2007; Kerwin and Irwin, 2010; Manning et al., 2011). Ĉuk et al. (2009) deemed the change in rotation during the flight of the Tkachev impressive and further divided the preparation and execution of the Tkachev into four phases: preparation (handstand to hang), release (hang to release), flight (airborne) and re-grasp. These four phases can be appropriately supplied to the performance of other release and re-grasp skills that have received kinematic, kinetic and energetic focus.

2.5.1 Kinematics

Arampatzis and Brüggemann (1999) reported equality in the shoulder and hip joint contributions to the successful execution of preparatory longswing preceding dismount and release and re-grasp skills. These authors also introduced the second extension-flexion phase at the shoulders and flexion-extension phase at the hips in the execution of the straddle Tkachev; where the kinematic characteristics were yet to be quantified. Hiley et al. (2007) examined the consistency of executing the release and re-grasp skill of the straddle

Tkachev within a specified release window. The release window was defined as the time in which the gymnast had appropriate linear and angular momentum to complete the re-grasp successfully (Hiley et al., 2007). One male national gymnast performed 60 Tkachevs where 10 successful and 10 unsuccessful trials were matched to a four segment planar simulation model to determine the release window. These authors found that contributing to achieving release within a particular release window were the joint angular kinematics prior to release. The timings of shoulder extension to flexion and hip flexion to extension were required to be executed at the correct time in order for release to fit within the calculated release window. Successful performances of the Tkachev within the study of Hiley et al. (2007) performed an earlier release by 6° with the hip extension occurring before shoulder flexion and continuing to extend and flex into the flight phase. The release findings of Hiley et al. (2007) concurred with that of Holvoet et al. (2002) who reported that when approaching release, an earlier release with lower vertical position (3.15 m compared to 3.21 m) and horizontal velocity of the centre of mass (-2.06 m.s compared to -2.35 m.s) promoted successful execution of the Tkachev with high vertical velocity and horizontal position.

An increase in joint angular velocity has been reported to increase angular momentum prior to release (Arampatzis and Brüggemann, 1998) and in addition the joint kinematics at release enabled an extended body configuration that increased angular velocity about the mass centre as the gymnast changed their body position to either straddle or pike through the flight phase and reduce their moment of inertia (Fink, 1988).

2.5.2 Kinetics

The principle of conservation of angular momentum states that a rotating body will continue to rotate with the same angular momentum until another eccentric force is applied to the rotating body to modify its angular motion (Hay, 1993). At the release point for flight elements on the uneven bars, the gymnast must therefore generate sufficient angular momentum preceding release to execute the skill successfully (Prassas et al., 2006). Through a forward dynamics approach, Hiley and Yeadon (2005) examined the release window available for female gymnasts to dismount the uneven bars successfully with sufficient linear and angular momentum. These authors investigated the influence of the low bar position and concluded that development of the female longswing was required in order to achieve a sufficient release window with sufficient angular momentum due to the delayed hip extension occurring after the gymnast had passed the vertical.

Applied to release and re-grasp skills, Hiley et al. (2007) inferred that the release window, compared to the previously investigated dismount skills, would be smaller and require greater accuracy due to the essential re-grasp to deem the skill successful. The linear momentum for example generated for release would require higher constraints compared to dismounts to ensure the gymnasts do not over shoot the high bar. Hiley et al. (2007) highlighted the importance of the timing of the previously reported shoulder and hip joint kinematics on the production of angular momentum for release and re-grasp skills. A late initiation of shoulder flexion and hip extension prior to release resulted in a delayed generation of angular momentum so that when sufficient angular momentum was achieved, horizontal velocity was in excess and re-grasp was not successful.

Fink (1988) reported the importance of the transfer of angular momentum and Newton's third law (action-reaction) in the successful release of release and re-grasp elements; the Jaeger and the Tkachev. The extension at the hip joints identified by Arampatzis and Brüggemann (1999) and Manning et al. (2011) prior to release in the Tkachev allows for the transfer of forward rotation from the lower limbs to the rest of the body (Fink, 1988). The reactive force on the high bar due to the extension at the hips and flexion at the shoulders contributes to additional torque at the high bar (Fink, 1988).

Holvoet et al. (2002) identified the importance of the lower limb contribution to the total body angular momentum (>50%) as the gymnast released and travelled over the high bar. The increased contribution to total angular momentum from the trunk and head were characteristic of unsuccessful Tkachev performance and therefore stabilising the upper limbs would be beneficial to successful performance (Holvoet et al., 2002). Further investigation into the segmental contribution to angular momentum required for female release and re-grasp skills is warranted due to the influence of the low bar and potential differences in segment angular momentum during the preparatory longswing compared to their male counterparts.

Kerwin and Irwin (2010) examined the musculoskeletal work preceding two variations of the same release and re-grasp skill; the inward and outward straddle Tkachev. These authors investigated differences in the joint kinetics by either negotiating the position of the low bar on the downswing or upswing. A key finding by the above authors was the varying shoulder contribution; in the more traditional outward facing Tkachev the musculoskeletal work at the shoulders was predominantly positive compared to negative in the inward facing technique. These kinetic characteristics of the inward technique

permitted favourable release parameters and greater reversal of angular momentum to perform the skill more effectively (Kerwin and Irwin, 2010).

2.5.3 Energetics

For the successful completion of release and re-grasp skills, sufficient starting energy is required which is generated by the preceding skill, the preparatory longswing (Arampatzis and Brüggemann, 1998; 1999). Arampatzis and Brüggemann (1998) investigated the efficiency of the preparatory longswing through the examination of the interaction of energy supplied through muscle action to the elastic high bar and the consequent utilisation properties. The above authors reported a transfer of energy from the gymnast to the high bar in the first phase of the preparatory longswing and constructed a criterion score during the downswing. If the increase in bar energy was less than the decrease in gymnast energy, the longswing technique was deemed inefficient and without advantageous implications. Ĉuk et al. (2009) similarly reported that as much energy as possible should be accumulated during the downswing (preparation phase) some of which is stored in the high bar.

Arampatzis and Brüggemann (1998) furthermore established a second criterion for the energy exchange during the upswing. To determine the utilisation of muscle capacity, an increase in gymnast energy greater than the decrease in bar energy represented a good movement execution. During the upswing the gymnast attempts to restore as much energy as possible and divide the total energy into the required amount of rotational and translator energy (Arampatzis and Brüggemann, 1999; Ĉuk et al., 2009).

Arampatzis and Brüggemann (1999) later applied the established energetic criterion on the uneven bars to examine the energy exchange between the gymnast and apparatus. The influence of the low bar for a female gymnast caused an inefficient criterion 1 with the passive shoulder flexion and hip extension not providing sufficient muscular energy. Gymnasts performing dismounts and the gienger release and re-grasp skill illustrated higher total energy at the start of the longswing than at release (Arampatzis and Brüggemann, 1999); however, the hip flexion during the upswing provided an increase in gymnast energy and an increase in criterion 2.

With further application of the criterion score, Arampatzis and Brüggemann (2001) focused on the straddle Tkachev and whether there was a possibility of energy gain by the preparatory longswing, previously not established in the gienger or dismount (Arampatzis and Brüggemann, 1999). With the introduction of a third criterion due to the additional shoulder flexion and hip extension prior to release, positive joint power resulted in

muscular energy and an increase in gymnast total energy, greater than the decrease in bar energy (criterion 3).

It has been noted that the gymnast can utilise the elastic properties of the bar and work with the recoiling nature in order to use the return of energy to pull them over the bar, particularly in the Tkachev (Prassas et al., 2006). Arampatzis and Brüggemann (1998) reported that the maximum bar force characteristics can infer how much energy is stored in the bar and identified that smaller joint angular velocities executed in the upswing produced less bending of the elastic high bar and consequently lower bar forces.

2.6 Methodological Approaches

2.6.1 Image Based Motion Analysis

Image based analysis systems traditionally dominate the field of biomechanics with objective video data strengthening the coaching-biomechanics interface (Elliott and Alderson, 2007). Within artistic gymnastics, manual digitising of video data has also dominated the data collection procedures (Kopp and Reid, 1980; Cheetham et al., 1984; Gervais, 1993; Kerwin et al., 1993; Witten et al., 1996; Arampatzis and Brüggemann, 1998; 1999; 2001; Yeadon and Hiley, 2000; Irwin and Kerwin, 2006; 2007; Kerwin and Irwin, 2006; 2010; Manning et al., 2011). Brewin and Kerwin (2003) stated the importance of accurate estimates of positional data and inferred to the implication of errors causing incorrect conclusions from analytical methods. Accuracy within the data collection procedure, processing and analysis is therefore crucial with the former being proven to be acceptably high with a precision of 2.5 x 10^{-3} m (Kerwin, 1995).

Although the female longswing has previously been classified with bilateral symmetry (Irwin and Kerwin, 2001), its two dimensional nature still requires three dimensional data collection techniques if an in depth, accurate analysis is to be carried out (Yeadon and Challis, 1992; Robertson et al., 2014). Within a competition environment, Brewin and Kerwin (2003) also highlighted the difficulty in an accurate camera position to incorporate a level horizontal and perpendicular position to the concerned movement utilising a two dimensional (2D) scaled approach. The field of view constructed must permit the full range of movement as well as allowing for extra frames before and after the required skill (Robertson et al., 2014). With the subject's image as large as possible within the field of view, care must be taken to ensure required landmarks for digitising do not pass too close

to the edge of the field of view as this may result in distorted image data (Robertson et al., 2014).

In order to reconstruct the 2D digitised image data to a 3D reference frame, known locations via a calibration frame are required to encompass the field of view and the performance area (Yeadon and Challis, 1992; Payton, 2008; Robertson et al., 2014) for 3D direct transformation (3D DLT) to occur. The above authors reported the minimum number of known locations as six for the accurate processing of 3D DLT, although 15 or more were recommended. By providing known coordinates for the accurate reconstruction process, camera position is more arbitrary compared to the 2D scaled comparison and therefore an advantage in the collection of elite competition data within an arena (Brewin and Kerwin, 2003). 3D DLT uses a minimum of 11 parameters for each camera that in turn are functions of geometric parameters; six defining the geometry of the camera and five defining the internal characteristics of each camera. In order to account for the curvature of the lens and provide lens correction, a twelve DLT parameter is often included (Brewin and Kerwin, 2003).

Through the differentiation of digitised coordinate data for the calculation of velocity and acceleration parameters, high frequency noise is unfortunately a common by-product (Robertson et al., 2014). Minor errors in digitising, together with the phase shift in the second derivative calculation results in a noise dominant second derivative (Robertson et al., 2014) and therefore the noise in the original positional data needs to be exposed to a noise removal method. Within gymnastics research there are two methods that are predominantly used; digital filters (Gervais and Tally, 1993; Brüggemann et al., 1994; Witten et al., 1996; Arampatzis and Brüggemann, 1998, 1999; 2001) and spline fitting (Kerwin et al., 1990; Kerwin et al., 1993; Yeadon and Hiley, 2000; Kerwin and Hiley, 2003; Hiley and Yeadon, 2003). The use of a digital filter requires a selected cut off frequency that allows for the preselected frequencies to be passed through the filter which effectively removes the effects of other frequencies (Winter, 2009). The selection of the specified cut off frequency is often determined through an analysis of the residual of the signal that determines the amount of signal filtering (Winter, 2009). The visual inspection of the residual-frequency graph provides an equal balance between signal distortion and the amount of noise allowed through the filter.

Image based analysis appears to be the most favourable approach within the competition environment of Women's Artistic Gymnastics due to absence of interference with the gymnasts or coaches within the field. Previous research comparing methods of data

collection that favour both the field and lab respectively have reported greater accuracy when collecting displacement data with an opto-reflective system for example (Ehara et al., 1995; Richards, 1999). However, the increase in accuracy within the above studies was minor with the error between known displacement values for the 50 Hz video data 0.6% and between 0.3 and 0.5% for the opto-reflective data. In order to maintain ecological validity and to collect data from an underrepresented elite data set, the use of image based motion analysis would be set as the preferred approach.

2.6.2 Kinetic Analyses

The determination of joint kinetics has been approached utilising two methods throughout the research of the longswing on high bar and uneven bars; the bar down and toe up method. Direct force measurements formulating the inputs to the bar down method of approach has been utilised by bar instrumentation with strain gauges (Kopp and Reid, 1980; Ishi and Komatsu, 1987; Arampatzis and Brüggemann, 1998; 1999; 2001; Irwin and Kerwin, 2006). In order to calibrate the strain gauges attached to the high bar, the above authors loaded known masses to the bar and the linear force-voltage relationship was calculated. Prior to the work of Kopp and Reid (1980) bar force data had not been utilised to the best of the authors knowledge and later the indirect methods of approach have taken precedence due to the unobtrusive nature within a training and competitive environment (Gervais, 1993; Kerwin and Hiley, 2003; Kerwin and Irwin, 2006; 2010).

Gervais (1993) initially investigated whether reaction force data at the bar could be accurately calculated through an inverse dynamics approach. Utilising positional data, Gervais (1993) estimated vertical force data to within 24% and horizontal force within 26% of directly measured bar forces. Differences were attributed to the estimated magnitude and location of peak force, with the recommendation of an analysis into the segmental influences and apparatus set up. Kerwin and Hiley (2003) later examined the use of bar displacement on the accurate estimation of reaction forces at the bar. With the high bar acting as a linear spring and therefore the displacement of the bar directly proportional to the load applied, bar stiffness coefficients were determined and applied to predicting bar force. Kerwin and Hiley (2003) estimated horizontal and bar forces within 3.5% with the tendency to over-estimate peak forces by 7%. This method compared favourably to the inverse dynamics approach of Gervais (1993) and within the field obtained differences between predicted and measured forces of 5.4%. Most recently, Irwin and Kerwin (2006) compared the methods taken by Gervais (1993) and Kerwin and Hiley (2003) with the addition of customised inertia parameters (Yeadon, 1990). Predicting bar forces through

the implementation of bar displacement produced errors up to 15% in the horizontal and 17% in the vertical, considerably larger than those predicted through inverse dynamics (up to 5% in the horizontal and 8% in the vertical). Kerwin and Irwin (2006) attributed the large differences in bar displacement estimations to the oblique camera view and the difficulty in determining the bar centre. These authors also concluded that with careful selection of inertia parameters and filtering procedures, the estimation of bar forces can be improved through inverse dynamics; an approach particularly suitable to elite competition collection.

2.6.2.1 Inverse Dynamics Analysis

Measuring internal joint forces to enable the researcher to determine the cause of human motion requires invasive and hazardous measurement techniques, therefore estimation methods are employed. Inverse Dynamics Analysis (IDA) provides a net measure of the internal joint forces and subsequent joint moments, powers and work; motion information that is unobservable by definition (Hatze, 2002).

Utilising Newton's second and third law of angular motion, multi-segmented inverse dynamics analysis can be conducted (Robertson et al., 2014). Illustrating the human performer as a segmental model aids in the determination of the joint kinematics and joint forces acting on the segments. Together with segment inertia parameters of those segments, these variables are classically computed to determine joint forces and moments (Robert et al., 2007). Hatze (2000) reported the importance of the segmental model used and the caution needed to ensure the model was not oversimplified but sufficiently adequate. Later, Hatze (2002) emphasised the importance of a valid simplified model preserving the segments replicative validity with the full kinematic chain of segments considered (Robert et al., 2007). It is imperative to note that the net joint forces or joint moments calculated from IDA are not that of an individual muscle unit (Hatze, 2000). The IDA procedure enables an estimation of the sum of the muscular action without a known distribution to particular muscles or motor units (Hatze, 2000; Robertson et al., 2014). IDA is therefore convenient for an evaluation of the relative effort of different joints and movements (Robertson et al., 2014).

The errors associated with IDA are well documented and numerous authors have highlighted the importance of the sensitivity of input data to IDA (Hatze, 2000; Hatze 2002; Yeadon and Challis, 1992; Challis and Kerwin, 1996; Riemer et al., 2008; Bezodis et al., 2013; Robertson et al., 2014). Hatze (2000) emphasised the dependence IDA has on the quality of experimental data and the adequate data processing methods. Errors commonly

linked to IDA inputs include the estimation of body segment inertia parameters (Challis, 1996; Challis and Kerwin, 1996; Kerwin and Irwin, 2006), inaccuracies within data collection (Richards, 1999) and data processing techniques (Bezodis et al., 2013) and the location of joint centres (Challis and Kerwin, 1996; Riemer et al., 2008).

The direct measurement of body segment inertia parameters (BSIP) for individual subjects is difficult to determine and therefore indirect methods are required. This highlights the potential of errors within the IDA procedure due to varying methods utilised in estimating BSIP values. The BSIP values required for an IDA analysis include segmental masses, mass centre locations and moment of inertia around the principal axes.

The cadaver data of Dempster (1955) obtained segmental mass and mass centre location data from the percentage of total body mass and percentage of segment length respectively. This ratio method was utilised by studies of Okamoto et al. (1987), Gervais and Tally (1993), Witten et al. (1996) and Holvoet et al. (2002). Previous research by Brüggemann et al. (1994) and Arampatzis and Brüggemann (1998; 1999; 2001) employed complex regression equations to determine BSIP parameters derived from gamma scanning methods (Zatsiorsky and Seluyanov, 1983). It was noted that the segmental mass values were often overestimated when compared to those of Dempster (1955). The geometric model of Yeadon (1990) has formed the determination of BSIP parameters for the majority of the remaining research within gymnastics (Yeadon and Hiley, 2000; Hiley and Yeadon, 2003; 2005; Irwin and Kerwin, 2005; 2006; 2007; Kerwin et al., 2007; Kerwin and Irwin, 2010). 95 anthropometric measurements were recorded to calculate 40 separate geometric solids that represented between 11 and 20 segments. Through the use of a series of geometric solids used to construct geometric models, subject specific BSIP are attainable.

Numerous authors have identified that the influence of moment of inertia data in particular is negligible on resultant joint moment calculations (Challis, 1996; Challis and Kerwin, 1996; Ren et al., 2008). The error analysis by Challis (1996) examined a range of frequency activities from moderately slow to fast and reported influences on joint moments less than 0.7%RMSD. This author also reported the inevitable propagation of error characteristic at the hip joint due to errors in BSIP estimation at the preceding joints. However, Challis (1996) suggested that errors in further kinetic calculations other than joint moments may see a bigger influence of BSIP estimations.

Characteristic of positional data is the presence of noise and although subjected to low-pass filtering, noise will remain amongst the signal and be anticipated to influence the resultant joint moments through IDA (Challis and Kerwin, 1996). Hatze (2000) attributed

errors associated to the IDA process to the dramatic amplification of small high frequency noise in the first and second derivatives; accentuating the need for an appropriate regularisation procedure. Bezodis et al. (2013) later supported this particular location of error stating that the unavoidable presence of noise in kinematic data due to digitising error would be further attenuated in acceleration data.

Previous studies have also examined the influence of filtering force and positional data at varying cut off frequencies (Kristianslund et al., 2012; Bezodis et al., 2013) and the resulting effects on joint moments around peak impact forces. Bezodis et al. (2013) highlighted this as a possible misinterpretation of the movement patterns analysed. The above authors reported that the common process of filtering kinetic data at a higher cut off frequency than kinematic data created rapid and excessive fluctuations in knee joint moment data during ground contact phase in sprint running. Bezodis et al. (2013) recommended that the application of the same cut off frequency should be employed when kinematic and kinetic inputs are required to IDA and that kinetic data should be filtered separately if discrete variables for example are required.

Challis (1999) identified the need of a repeatable procedure that provides an objective estimate for the optimal frequency cut off. The author acknowledged those completed by visual inspection or the use of previous cut of frequencies, however suggested that they had a lack of objectivity. Challis (1999) therefore presented a new procedure that automatically determined the cut off frequency, the autocorrelation based procedure, through the best approximation of white noise determined by the autocorrelation function; providing a more objective alternative to the determination of cut of frequencies.

Challis and Kerwin (1996) identified that uncertainties in the kinematic inputs to IDA were key to the sensitivity of joint moment calculations. The estimation of joint centre location through both a digitising or marker placement procedure provided the point through which the internal joint force was applied, determining the resultant joint moment. Challis and Kerwin (1996) reported differences between the original and perturbed joint centre locations as less than 0.8 Nm, however with standard deviations higher than the mean differences, sensitivity of the kinematic variables and therefore influence on joint moment data were reported as high.

Riemer et al. (2008) conducted a sensitivity analysis on the uncertainties in IDA with an application to gait analysis. These authors reported uncertainties in joint moments between 6 and 232% in walking gait and attributed these findings to marker movement and therefore the determination of joint centres. Riemer et al. (2008), similarly to Challis and

Kerwin (1996) highlighted that the comprehensive analyses carried out were specific to the specific to the activity. These authors emphasised the applicability and possible adaptation of the reported protocol to other movements, a prerequisite to the calculation of joint moments and subsequent joint kinetics.

When the estimation of joint moments and segmental energies are required, an error analysis should always be executed in an attempt to quantify the errors associated with the measurement (Yeadon and Challis, 1992; Hatze, 2002). However, it is not possible to compare estimated results from IDA to 'gold standard', known measures (Hatze, 2002; Robert et al., 2007) and therefore validation or closeness of agreement to other predicted methods are required. With the above authors reporting that some sources of error are less significant than others, data treatment techniques and BSIP estimates are paramount. With this in mind, Robertson et al. (2014) emphasised that when comparing across studies, a 10% margin of error should be permitted.

2.7 Chapter Summary

The following summary provides an overview of the chapter and an explanation of the thematic approach adopted throughout the thesis. This chapter has provided an insight into the existing literature surrounding the biomechanics underpinning the longswing and technique selection. Research has predominantly focused on the men's version of this skill with some indications of the influence of the position of the low bar on the women's longswing technique. The application of previous research to the mechanics of the female longswing therefore requires a rise in in-depth knowledge to fully understand the female longswing technique and its variations.

The review of literature has informed the development of the overall aim of the thesis: to increase the knowledge and understanding of the biomechanics underpinning the techniques of the female longswing in artistic gymnastics for the determination of effective technique selection. The five themes to achieve this research aim were developed and a series of research questions addressed within four studies (Chapters 3-6).

Research over the last three decades across Men's and Women's Artistic Gymnastics has utilised elite competition data (Kerwin et al., 1993; Arampatzis and Brüggemann, 1998; 1999; 2001; Hiley and Yeadon, 2005; Kerwin et al., 2007; Ferreirinha et al., 2010; Kerwin and Irwin, 2010; Naundorf et al., 2010; 2011; Manning et al., 2011) and promoted high levels of ecological validity. Theme 1, **Contemporary Trend Analysis**, extends this

characteristic of previous literature with the use of competition data from the Olympic Games and World Championships forming the basis of this thesis. Ferreirinha et al. (2010; 2011) reported an extensive trend analysis across four Olympic cycles contributing meaningfulness and composition to the existing body of knowledge, a purpose of Theme 1 within the current thesis.

Varying techniques to perform the same skill have been identified and examined across different apparatus in artistic gymnastics (Kerwin et al., 1993; Hiley et al., 2009; Kerwin and Irwin, 2010; Naundorf et al., 2010; Farana et al., 2013). Employing a **Biomechanical Conceptual Approach**, Theme 2 quantifies differences between techniques that Lees (2002) defined from a biomechanical perspective as the relative position and orientation of body segments as they change during the effective performance of a task. Previous literature has examined the joint kinematics and angular momentum characteristics of the longswing (Borms et al., 1976; Boone, 1977; Cheetham, 1984; Arampatzis and Brüggemann, 1998; 1999; 2001; Kerwin, 1999; Yeadon and Hiley, 2000; Holvoet et al., 2002; Hiley and Yeadon, 2003; 2005; Irwin and Kerwin, 2005; 2006; 2007; Kerwin et al., 2007; Sheets and Hubbard, 2007; Kerwin and Irwin, 2010; Manning et al., 2011), but with dominant focus on the male version, scope to apply the implications of previous research to the female longswing and its varying techniques was established and developed the previously reported research.

To extend the depth of knowledge and understanding of longswing technique, the biomechanical demands required examination that would in turn surmise the physical demand placed on the gymnast. However, non-invasive methods to collect joint kinetic data are challenging, increasingly so within an elite competition environment, highlighting the requirement for indirect methods. Theme 3, **Method Validation**, builds on from previous sensitivity analyses of inverse dynamics (Challis and Kerwin, 1996; Hatze 2000; 2002; Robertson et al., 2014) to rationalise the proposed method of approach within the field. In addition, a novel field versus lab comparison analysis developed from the findings of Elliott and Alderson (2007) provides validation of the methods employed within the subsequent themes.

Research into the musculoskeletal characteristics of the longswing has further enhanced the understanding of the longswing from a joint kinetic perspective (Arampatzis and Brüggemann, 1999; Yeadon and Hiley, 2000; Irwin and Kerwin, 2005; 2007; Kerwin and Irwin, 2010). However, with changes in the apparatus and scoring system for female gymnasts at the beginning of the 21st century, timely development of the research to the

musculoskeletal demands of the female longswing would be necessary. The **Biomechanical Musculoskeletal Approach** of Theme 4 therefore provides an increase in the knowledge and understanding of the biomechanics underpinning the female longswing.

Previous research into the energetic demands of the longswing has been dominated by the criterion score of Arampatzis and Brüggemann (1998; 1999; 2011). Through the **Biomechanical Energetic Approach,** Theme 6, the energetic contribution from the gymnast to the gymnast-high bar system will be investigated. Examining varying energetic demands across techniques enables the determination of effective technique selection, concluding the thematic approach to addressing the overall thesis aim.

CHAPTER THREE

TREND ANALYSIS OF RELEASE AND RE-GRASP SKILLS AND THE PRECEDING LONGSWING TECHNIQUE

3.1 Introduction

The evolution of Women's Artistic Gymnastics has seen the rapid increase in difficulty and the inclusion of complex elements, both of which have been driven by the change in the Code of Points in 2006 (Federation Internationale de Gymnastiques [FIG], 2009). With the desire to include higher difficulty within elite performances, gymnasts have increased the variations of particular release elements by performing different entries or different movement patterns throughout the somersault. As well as increasing the start value of the gymnast's routine, these advances also contribute to the linking and execution of combination skills, again exuberating complexity (Arkaev and Suchilin, 2004).

In conjunction with the number of different ways the same release element can be performed, gymnasts are able to execute the swinging movements prior to the same skill differently. Uneven bar performances in Women's Artistic Gymnastics vary from that of their male counterpart through the added necessity to negotiate the location of the low bar. Female gymnasts have a number of options in passing the low bar effectively and completing circling skills successfully in attempt to surpass the constraints of the low bar. Varying longswing techniques are subsequently used on the uneven bars in Women's Artistic Gymnastics but detail into these differences between longswings is unknown.

As previously discussed in Chapter 2, the basic technique of the backward longswing requires the gymnast to make adjustments to the shoulder and hip joints as they rotate around the bar (Borms et al., 1976; Yeadon and Hiley, 2000) and this is emphasised by previous studies that suggest the paramount importance of the shoulder and hip motion in the success of this skill (Arampatzis and Brüggemann, 1999; Yeadon and Hiley, 2000; Irwin and Kerwin, 2005; Hiley and Yeadon, 2007). When manipulating their body shape through adjustment of the shoulder and hip joints, the gymnast aims to optimise angular momentum and the transfer of energy into the high bar as well as clear the low bar in order to complete the following complex skills (Hiley and Yeadon, 2005). Achieving sufficient angular momentum for release and dismount skills is a key function of the backward longswing, with another being to link circling skills (Hiley and Yeadon, 2003).

A key concept to this investigation was that there are numerous longswing techniques preceding the performance of the same skill which suggests that there may be a number of factors that determine the choice of longswing executed. This observation of different techniques caused the following questions to arise;

- What release and re-grasp skills are performed by elite female gymnasts during International competition?
- What longswing techniques are used to precede the selected release and re-grasp skills?
- What are the factors that influence the selection of longswing technique prior to release and re-grasp skills?

The first aim of this chapter was to identify and develop knowledge of varying longswing techniques and the preceding skill used by elite female gymnasts. In addition, the second aim of this chapter was to increase understanding of the influencing factors of gymnast stature, mass and nationality on technique selection. These aims and the consequent research questions constructed Theme 1: Contemporary Trend Analysis, integrating high ecological validity with meaningfulness and confidence in the subsequent research findings.

3.2 Method

3.2.1 Participants

Data were collected during the qualification rounds at the 2000 Sydney Olympic Games and the 2007 Stuttgart World Championships. Video image data were recorded as part of the IOC medical commission and as an FIG approved research project for each of the respective International competitions. The contribution of the principle investigator (PhD candidate) to data collections was focused on the discussion of equipment set up and protocol for the 2007 Stuttgart World Championships. The principle investigator completed data processing, analysis and interpretation independently. The above contribution of the principle investigator was consistent across Chapters 3, 4 and 6 where the elite competition data were utilised. In Chapter 5 the principle investigator carried out all data collection, processing, analysis and interpretation independently.

Each of the 82 qualification routines from Sydney and 117 from Stuttgart were observed and the age (17.7 ± 2.8 years), height (1.54 ± 0.07 m) and body mass (45.12 ± 6.88 kg) of the elite gymnasts, together with nationality, were recorded. Attire was consistent throughout the sample of gymnasts with an FIG approved leotard worn. Informed consent was gained at the source prior to data collection.

3.2.2 Data Collection

Video image data were obtained from two video cameras (Sony Digital Handycam DCR VX1000E) operating at a frequency of 50 Hz. Digital images were played back using a Sony HDV 1080i DVCAM. This study focused on the accelerated longswing which aims to increase angular momentum in order to prepare for release and re-grasp elements (Kerwin, 1999) as opposed to the general longswing. This is due to the investigation focusing on gymnasts negotiating passing the low bar as well as maintaining and optimising biomechanical variables (i.e. angular momentum, angular velocity). Therefore, backward longswings analysed were those that preceded a release and re-grasp element.

3.2.3 Data Protocol

A qualitative frequency analysis was conducted by describing longswing techniques that were performed during the two International competitions. Different longswing techniques were established through visual inspection via digital recordings of differences in shoulder and hip movements. Categories and mutually exclusive variants within those categories were determined to establish a protocol for technique identification.

Shoulder joint angles were distinguished by an imaginary vector connecting the hip, shoulder and elbow joints, with extension consisting of closing the joint. Similarly for the hip joint, a line connecting the knee, hip and shoulder defined the joint with opening of the joint demonstrating extension. Full flexion at the shoulder joint and full extension at the hip joint was defined as 0°.

Shoulder characteristics were grouped by two categories; degree of shoulder extension and location of shoulder flexion in relation to the low bar. Observed shoulder angles enabled the degree of shoulder extension to be determined and were classified as either 0°, 45° or 90° angles. Figure 3.1 illustrates two backward longswings with the degree of shoulder extension in the first quarter of the longswing at 45° (Figure 3.1a) and 0° (Figure 3.1b). For both longswing techniques illustrated, hip extension was initiated above the low bar.
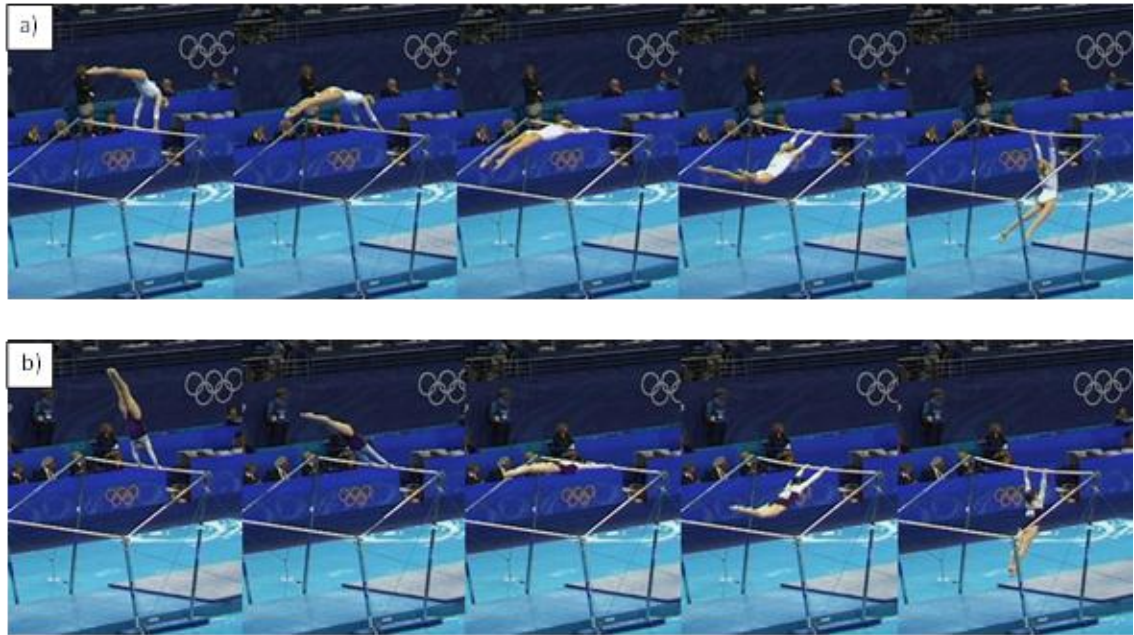
Figure 3.1. Variations of longswing technique preceding release elements a) 45° shoulder extension, hip extension above low bar b) 0° shoulder extension, hip extension above low bar.

Hip characteristics were similarly categorised into degree of hip flexion, presence of hip abduction and location of hip extension in relation to the low bar. Variants of hip flexion consisted of an observed 0°, <45° and >45° hip angle illustrating the straight, dish and pike longswing respectively (Figure 3.2). Sub-categories of abduction were no abduction, abduction and abduction in extension that allowed the presence of leg separation in the frontal plane to be identified. Finally, the location of maximum hip extension was recorded to be either above or below the low bar.

Figure 3.2a illustrates a backward longswing with 0° hip flexion, abduction and then hip extension below the low bar. Figure 3.2b illustrates a similar technique however there is flexion of less than 45° in the first quadrant of the longswing. The extreme variant of degree of hip flexion (> 45°) is illustrated in Figure 3.2c with a pike longswing being performed. The pike technique also differs from the previous two due to no abduction of the legs being present. However, all three do demonstrate hip extension after they have passed the low bar. With the above categories and sub categories defined, the varying female longswing techniques were recorded.
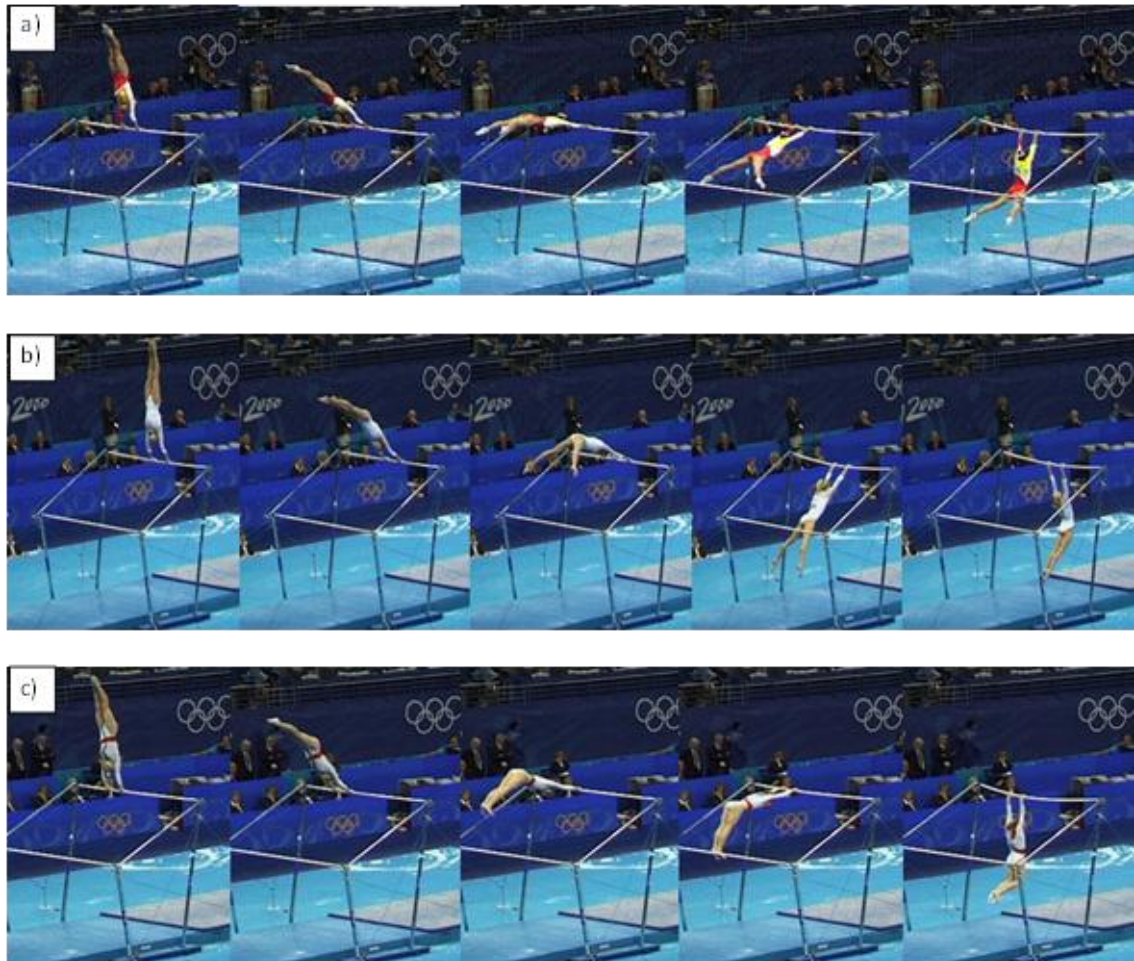
Figure 3.2. Variations of longswing technique preceding release elements a) 0° hip flexion, abduction b) <45° hip flexion, abduction c) >45° hip flexion, adduction.

3.2.4 Data Analysis

The trend analysis was initiated by identifying the release and re-grasp skills performed by elite female gymnasts. Determining which release and re-grasp element the identified longswing preceded allowed the distinction of whether the preparatory longswing was either forwards or backwards and the direction of rotation of the following skill. Distinguishing these factors concurs with the four classes of preparatory longswings identified by Brüggemann et al. (1994). Each release and re-grasp skill was recorded and if the re-grasp was not successful, the trial was deemed unsuccessful.

Longswing techniques were established and reported by employing the previously defined characteristics at the shoulder and hip joints (section 3.2.3). The identified longswing techniques were subsequently grouped accordingly to gymnast nationality, gymnast stature and gymnast mass in order to determine any trends between longswing technique and potential influencing factors. Longswing techniques used by specific nationalities were

identified by grouping gymnasts according to their continent of origin. The sub categories consisted of America, Western Europe, Eastern Europe and Asia. Gymnast stature, represented by gymnast height, and mass were collated into quartiles and any trends of the influencing factors reported.

3.3 Results

Based on the classification of release and re-grasp elements by Brüggemann et al. (1994), the frequency of flight skills and the corresponding direction of longswing are presented in Table 3.1. The most frequently performed release and re-grasp skill that followed from a backward rotating longswing was the straddle Tkachev (53%).

Table 3.1. Frequency of release and re-grasp skills in the combined 2000 Sydney Olympic Games and 2007 Stuttgart World Championships (B = Backward, F = Forward, O = Outward, I = Inward)

Skill	Longswing	Inward	Outward	Somersault	Relation to bar	Frequency
Straddle Tkachev	B	26	48	F	O	74
Toe On Tkachev	B	9	0	F	O	9
Stalder Tkachev	B	1	0	F	O	1
Pike Tkachev	B	1	0	F	O	1
Geinger	B	1	49	B	I	50

The varying movements at the shoulders and hips, defining the different longswing techniques that preceded the straddle Tkachev, are illustrated in Figure 3.3. One of the key variants observed that enabled the gymnasts to eliminate the influence of the low bar on the descent phase of the preparatory longswing was performing the skill in the opposite direction. Thirty five per cent of straddle Tkachevs executed were performed in the less traditional inward direction; swinging towards the low bar and travelling away from the low bar during the flight phase. For the remaining 65% of the preceding longswings, changes at the shoulders and hips occurred in order to negotiate the location of the low bar during the descent phase. Slight hip flexion ($< 45°$) was the dominant hip position on the downswing with 40% of the longswing illustrating this dish position. $0°$ hip flexion and maximum hip flexion ($> 45°$) were similarly frequented with 31% and 29% of the backward longswings employing these techniques respectively (Figure 3.3).
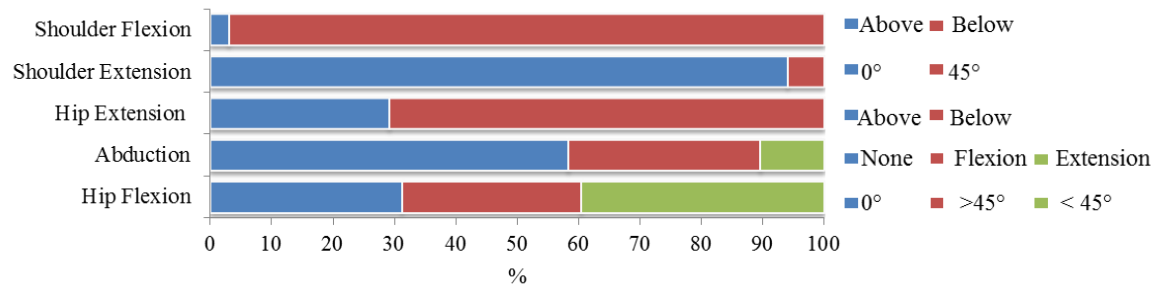
Figure 3.3. Variations in longswing technique for the outward straddle Tkachev preparatory longswing.

In conjunction with the degree of hip flexion adopted by gymnasts in the backward preceding longswing, the performance of leg abduction was also a contributing factor to varying longswing techniques. Fifty eight per cent of the elite gymnasts executed no leg abduction with the remaining 42% performing a straddle longswing. Three quarters of the gymnasts who performed a straddle longswing executed early leg abduction combined with hip flexion whereas the final quarter revealed a straddled arch technique with leg abduction occurring in conjunction with later hip extension.

Distinguishing the arch longswing technique over the other variations was performing hip extension prior to passing the low bar. Twenty nine per cent of elite gymnasts initiated hip extension above the low bar whereas the residual 71% performed hip flexion or no movement at the hips before extending at the hips nearer the bottom of the longswing.

Figure 3.3 illustrates the dominant movement of the shoulders and location of shoulder flexion in relation to the low bar during the descent phase of the preceding longswing. Dominant movement combined 0° shoulder extension with shoulder flexion occurring after the gymnast has successfully passed the low bar. Six per cent of backward longswings executed shoulder flexion prior to passing the low bar and a smaller 3% performed a closed shoulder angle during the descent phase before passing the low bar and reaching shoulder flexion.

The differences observed in shoulder and hip movement patterns performed in the backward longswing enabled the differentiation of longswing techniques employed by elite female gymnasts. From the categories and sub categories illustrated in Figure 3.3, six longswing techniques were established (Table 3.2). For the six defined longswing techniques the influence of nationality, gymnast stature and mass were examined.

Table 3.2. Characteristics of varying longswing techniques preceding the outward straddle Tkachev

Longswing	N = 48	Hip Flexion	Hip Abduction	Hip Extension
Dish	10%	0 - 45°	None	Below low bar
Arch	19%	0 - 45°	None	Above low bar
Straddle	35%	0 - 45°	During hip flexion	Below low bar
Pike	31%	> 45°	None	Below low bar
Arch Straddle	4%	0 - 45°	During hip extension	Above low bar
Pike Straddle	1 inward	> 45°	During hip flexion	Below low bar

Nationality

Longswing techniques varied considerably across different continents with particular techniques being predominantly executed by particular nations. The arch technique, hip extension above the low bar, was performed by 50% of the Eastern European gymnasts. The remaining gymnasts from this region were divided similarly into performing the dish, pike and straddle techniques (approximately 15% for each technique) with a single arch straddle technique being performed. Similarly, however not in the same magnitude, the arch technique was a common technique performed by gymnast's competing in an Asian team. Twenty five per cent of Asian gymnasts performed the arched longswing; however, they predominately adopted the straddle technique (44% of gymnasts). The remaining Asian gymnasts employed either a dish (13%) or pike (19%) approach (Figure 3.4).

A similar selection of longswing techniques for the Western European and American elite gymnasts were observed. Figure 3.4 illustrates the dominance of the straddle and pike techniques for both continents. Thirty eight per cent of Western European gymnasts and 42% of American gymnasts adopted the pike technique and 31% and 26% the straddle technique respectively.

Investigating the characteristics of each nation, the Eastern European gymnasts were classified as the shorter gymnasts (making up 44% of the lower quartile) closely followed by the Asian gymnasts that made up 39% of the second quartile. The American gymnasts were evenly distributed throughout the height ranges and the Western European gymnasts contributed to 35% of the tallest gymnasts (1.58-1.73 m).
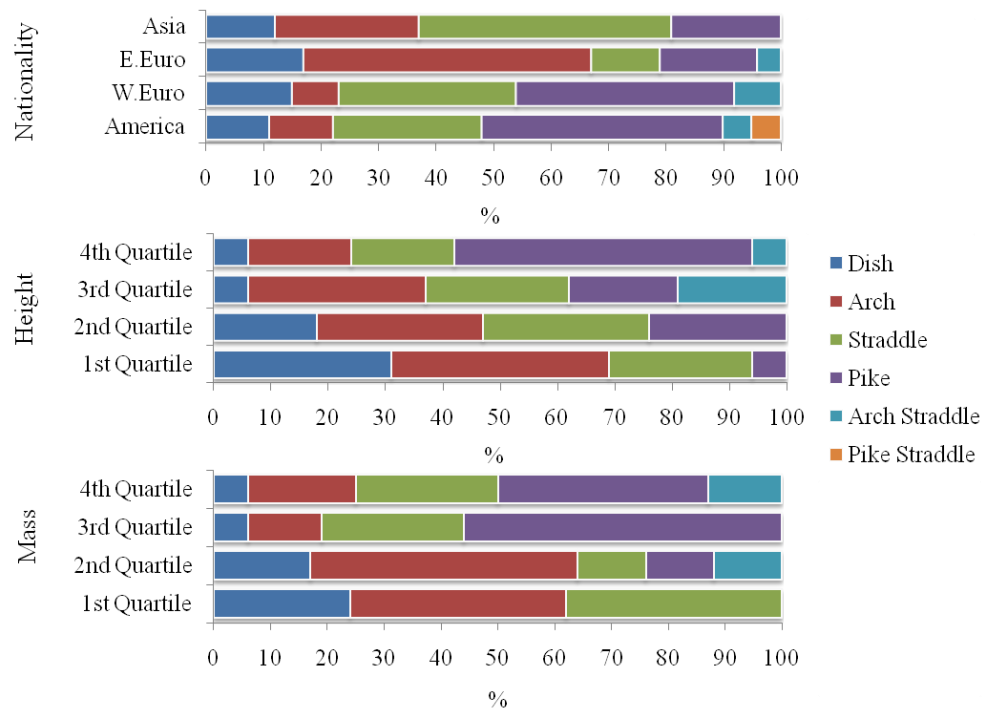
Figure 3.4. Trend analysis of varying longswing techniques when grouped according to a) nationality, b) height and c) mass.

Stature

When observing the relationship between female longswing technique and gymnast height, the degree of hip flexion and therefore technique adopted increased throughout the height quartiles (Figure 3.4). Gymnasts in the lower quartile (1.39 – 1.48 m) distinctly adopted techniques with 0-45° hip flexion performing either an arch (38%), dish (31%) or straddle (25%) technique. The remaining 6% of the shorter gymnasts competed with hip flexion greater than 45° and therefore the pike longswing. The inter quartile range (gymnasts with a height between 1.48 and 1.57 m) were very similar in the longswing techniques selected (Figure 3.4). With 2-5% separating the second and third quartiles in the proportion of arch, straddle and pike longswings selected, the key difference was the inclusion of the straddle arch technique for the taller of the two groups (6%). Finally, the tallest of the elite gymnast fell between 1.58 and 1.73 m. The greatest degree of hip flexion during the descent of the longswing was observed here with 52% of the gymnasts performing a pike technique. The longswing techniques with less than 45° hip flexion made up the remaining half of the techniques chosen but were categorised into four other less favoured techniques; the dish (6%), arch (18%), straddle (18%) and straddle arch (6%).

Mass

When grouped according to gymnast mass, two distinct techniques appear to be favoured across the different quartiles (Figure 3.4). Gymnasts of a lighter mass (31-38 kg) adopted one of three techniques; dish, arch or straddle. The arch and straddle techniques each made up 38% of the selected population with the dish longswing completing the remaining 24%. Gymnasts in the lower quartile did not perform the pike longswing preceding a straddle Tkachev. Gymnasts in the second quartile (39-44 kg) predominately performed the arch longswing contributing to 47% of the selected group. The remaining half was divided evenly into gymnasts performing the dish, straddle, pike and arch straddle longswings. Gymnasts in the higher half of the inter quartile range had the highest percentage of pike longswings performed. Fifty six per cent of the population selected hip flexion greater than 45° as the technique to pass the low bar. Finally, the grouped gymnasts with greater mass, 49-68 kg, predominantly selected the pike longswing (37%). Similarly to gymnast height, as the gymnasts mass increased, there was a trend for the degree of hip flexion to also increase and therefore the increased selection of the pike longswing technique.

3.4 Discussion

The aim of this chapter was to identify and develop knowledge of longswing techniques employed by elite female gymnasts during International competitions. A frequency analysis of different preparatory longswing techniques aimed to establish the key techniques executed and to provide an insight into whether an association between gymnast stature, gymnast nationality and the techniques selected could be quantified.

Of the 199 qualification routines analysed from the Sydney 2000 Olympic Games and the Stuttgart 2007 World Championships, 70% of the routines consisted of a release and re-grasp element preceded by a backward longswing. The inclusion of more complex skills such as release and re-grasp elements have provided gymnasts with the athletic growth of complexity required to keep up with the demands of the ever evolving sport (Arkaev and Suchilin, 2004). The fundamental importance of the preceding longswing is therefore apparent in order to achieve sufficient angular momentum (Hiley and Yeadon, 2003) and correct release parameters for the following skills to be successful. Insight into varying longswing techniques and how each technique differs in this contribution is essential. Identifying which longswings are being employed at this stage by elite gymnasts will

provide the platform to accelerate into identifying why particular techniques should be chosen over others, enhancing technique selection.

Fifty three per cent of the backward longswings were followed by the straddle Tkachev with four different release and re-grasp skills making up the remaining 47%. The straddle Tkachev has therefore been utilised as the element that followed the longswing techniques analysed.

The distinct spatial and temporal characteristics of the shoulder and hip joints enabled categories of longswing techniques consisting of mutually exclusive variables to be established (Borms et al., 1976). The main differences in technique were differentiated by the degree of hip flexion, abduction of the legs in the frontal plane and location of hip extension relative to the low bar. As previously established in Chapter 2, the movement patterns at the shoulder and hip joints are key variables determining the success of the backward longswing (Arampatzis and Brüggemann, 1999; Yeadon and Hiley, 2000; Irwin and Kerwin, 2005; Hiley and Yeadon, 2007).

Forty per cent of gymnasts competing at the two selected International competitions favoured the backward longswing with a hip angle between 0° and 45° during the descent phase. Techniques with hip flexion executed at 0° and greater than 45° prior to passing the low bar were similarly matched with 31% and 29% of gymnasts performing the respective techniques. The ratio of longswing techniques illustrating abduction to those with no abduction was 41% to 59%. Finally, the third group (hip extension location) revealed 29% of longswing techniques reaching hip extension above the low bar and 71% below the low bar. By manipulating their body position in the above manner to enable them to surpass the lower rail successfully, distinct techniques for elite gymnasts were reported. With key techniques apparent, the association between longswing technique and influencing factors were investigated.

For the straddle Tkachev, shoulder characteristics remained consistent for all gymnasts. There were no reported differences between longswing technique and nationality, stature or mass, with the vast majority of gymnasts descending into the longswing with 0° shoulder angle and executing shoulder flexion after passing the low bar (Figure 3.3). Although the movement patterns surrounding the shoulder joints have been deemed essential in successful longswing completion (Kerwin and Irwin, 2010), these results indicate the need for more detailed analyses to examine the more complex movement patterns (Williams et al., 2012). With the need to control their body position to overcome the low bar, female gymnasts may end up masking their shoulder movement due to the

limited space available to them compared to their male counterparts, who have been heavily researched. Ninety four per cent of gymnasts executed maximal shoulder flexion below the low bar; however, with further detailed kinematic analysis, circle angle location of this movement may enable technique variations to be explained. Irwin and Kerwin (2005) reported the importance of maximum shoulder flexion in establishing the initiation of the functional phase at the shoulders. The rapid hyper flexion to extension at the shoulders together with hyper extension to flexion at the hips defines the functional phases that underpin the success of the skill (Irwin and Kerwin, 2005). This phase was deemed functional due to the fundamental energetic input from the gymnast to complete the longswing occurring within this phase (Irwin and Kerwin, 2007) and dominantly at the shoulders for male gymnasts. Greater accuracy in locating the angular position of the gymnast during the functional phase at the shoulders may provide insight into possible shifts in the functional phases and how these change as a function of gymnast nationality and gymnast stature. This information may be useful to coaches in determining where to emphasis the arch and dish positions during the longswing and therefore selecting the technique they employ. Knowing where these phases occur can also help coaches develop a mind-set of the skill, which has been reported as a central component of successful skill development (Irwin et al., 2005).

The similarity across all of the female gymnasts in these results regarding shoulder characteristics highlights the possible importance in timing of the shoulder movement patterns and not solely the degree of flexion-extension. An investigation into the consistency of the movement at the shoulders together with angular velocity profiles at these specific joints may provide further explanation into the variation in longswing techniques.

When observing the relationship between longswing technique and gymnast nationality, key differences were reported. Fifty per cent of Eastern European gymnasts performing the straddle Tkachev illustrated hip extension prior to passing the low bar. When employing the definitions of the functional phase by Irwin and Kerwin (2005), similar coaching background across Eastern Europe appear to encourage gymnasts to initiate earlier hip extension in their longswing technique and consequently may have the effect of benefiting from an increase in the generation of angular momentum. Earlier hip extension has been reported to influence the angular momentum for the straddle Tkachev (Hiley and Yeadon, 2005). Changes in hip extension may be as a consequence of the necessity to pass the low bar effectively. Through observation there is no evidence to say that the hip extension

observed is maximal and therefore the start of the hip functional phase. Further kinematic analysis is required to determine angular velocity profiles at the hips to distinguish clearer differences in techniques. Angular velocity profiles enable the identification of the start and stop of the functional phases (Irwin and Kerwin, 2005). The role of the hip in the successful performance of these skills has been identified as fundamental for the generation of optimal angular momentum (Holvoet et al., 2002; Hiley and Yeadon, 2005).

Forty four per cent of gymnasts of an Asian nationality performed hip abduction during the descending phase of the preparatory longswing. Sheets and Hubbard (2007), through a forward dynamics approach, reported advantages of developing longswing technique to include abduction. Dismount performance (dismount revolutions) increased with hip motion occurring in the frontal plane of movement. However, the technique of the straddle Tkachev preceding longswing has to accommodate the change in the direction of angular momentum prior to release to generate forward rotation in the straddle Tkachev (Brüggemann et al., 1994). Release parameters between these two skills will therefore be different and cause uncertainty into whether hip abduction differences in longswing technique will be as advantageous for release and re-grasp skills. The presence of leg abduction in techniques by the Asian gymnasts highlights a possible influence of gymnast nationality on longswing technique, but similar to previous findings would require further analysis to examine the abduction influences on the parameters underpinning successful performance.

Gymnast stature was examined in relation to longswing technique employed. The taller gymnasts whose heights ranged from 1.58 - 1.73 m employed the pike longswing with legs together and hip angles greater than 45°. In comparison, Arampatzis and Brüggemann (1999) and Hiley and Yeadon (2005) both reported benefits of passing the low bar in an extended position. An extended body configuration has reported to increase angular momentum in the descent (Hiley and Yeadon, 2005) and increase energy storage into the elastic bar (Arampatzis and Brüggemann, 1999). The pike technique option employed by gymnasts in the upper quartile in the present study may prevent the gymnasts from obtaining these optimal values. Gymnasts in the upper quartile range would be required to change their body position to a greater extent and this appears to favour flexion at the hips greater than 45°. In general, gymnasts in the lower quartile with heights between 1.39 and 1.48 m were able to pass the low bar in a more extended position than the previously discussed group, performing either an arch, straight or dished technique.

The final difference between the two groups with different heights was the extension of the hips in relation to the low bar. The observed hip extension occurred above the low bar for 38% of the shorter gymnasts and only 18% of the taller gymnasts. Gymnasts in the lower quartile were able to pass the low bar in full extension enabling the gymnast to only require a small change in hip angle to initiate the hip functional phase. Similarly to the nationality analysis, it would be beneficial to develop the analysis to locate the exact location of the functional phases and establish any mechanical advantages that may be due to this technique. Determining whether an earlier hip functional phase occurs or whether it is a different technique in reaching an already established optimal location will provide further insight into different longswing techniques and a potential technique selection process based on stature.

Another aspect of this comparison is the recent increase in bar spacing that has allowed gymnasts to alter the direction of the longswing and therefore the following flight element (Kerwin et al., 2007). For the execution of a release and re-grasp element the gymnast has the option of facing the low bar and having to negotiate its position on the upswing as opposed to the downswing. Kerwin et al. (2007) reported release angular momentum 52% higher in the more recent technique than the more traditional technique. The inward facing longswing preceded 35% of straddle Tkachevs in this investigation, producing a further varying technique of the backward longswing. Further kinematic and kinetic analyses would be required to distinguish where these changes in technique occur due to altering the direction of the longswing.

Similarly to the hip joint, shoulder flexion above the low bar indicates the initiation of the previously defined functional phase. The closing of the shoulder angle in the first quadrant causes a change in the body position of the gymnast during the downswing that could affect the related biomechanical variables underpinning successful execution. Both of these factors require further analyses in order to quantify the effect they had on longswing technique and subsequently the following skill.

In response to the three questions constructed at the start of this study, it was important to identify the distinct longswing techniques employed by International gymnasts. With substantial differences occurring at the hip joints in particular, the three key techniques observed to facilitate the straddle Tkachev were the arch longswing, the straddle longswing and finally the pike longswing.

An influence of gymnast nationality and gymnast stature was apparent, however, further investigation to substantiate their influence is required. For example, Arkaev and Suchilin

(2004) highlighted the importance of how the link between body size and performance needs to take into account not only the demand but also the opportunity particular physical characteristics may provide gymnasts.

3.5 Conclusion

This study has highlighted the variations in longswing technique that were performed by elite female gymnasts during the 2000 Olympic Games and the 2007 World Championships. Differences in technique originated from the degree of variation at the two dominate joints, the shoulders and hips. By manipulating the movement patterns occurring around these joints, different strategies for passing the low bar were established. From this investigation, the contribution of the hips exceeds that of the shoulders considerably. The dominant role of the hip determines the differences in longswing technique that vary primarily due to the following variables;

- Hip extension in relation to the low bar

- Degree of hip flexion in the first quarter of the longswing

- Abduction of the lower extremities

- Direction of the preceding longswing

Although three key techniques were observed (arch, straddle and pike) it is essential to quantify the influence of the above variables in order to present an explanation to their occurrence and verify the technical requirements of the varying techniques. Further investigation engaging kinematic analyses will allow a more detailed differentiation between techniques and aid an understanding into whether one technique is more beneficial than another. From a coaching perspective, visual analysis is a key and immediate tool available within the training environment. Applying a further mechanical analysis will help to reduce the imitation of champions, educated guess work and trial and error methods of coaching, particularly for establishing a technique selection criterion (Cross and Lyle, 2002). Theme 1: Contemporary Trend Analysis has created an initial platform for the analyses that are further required whilst initialising a high level of ecological validity within an elite, competitive environment. With differences in technique established, Theme 2: Biomechanical Conceptual Approach was facilitated to explain the coach's differentiation of longswing techniques through scientific biomechanical underpinnings to increase knowledge and understanding of the female longswing.

CHAPTER FOUR

KINEMATICS AND ANGULAR MOMENTUM ANALYSES OF LONGSWING TECHNIQUES PRECEDING THE STRADDLE TKACHEV

4.1 Introduction

Chapter 3 has identified that the most frequently performed release and re-grasp skill utilising the backward longswing at the beginning of the 21st century was the straddle Tkachev. Fundamental to the success of this flight element is the preceding longswing and reported in the previous chapter are the variations of this skill. The backward longswing with hip extension (arch), lower limb abduction (straddle) or hip flexion (pike) prior to passing the low bar during the downswing were the three most common distinctive techniques used by elite female gymnasts preceding the straddle Tkachev. Although these distinct techniques have been observed in the previous chapter, it is essential to quantify the influence of the varying movement patterns to determine potential different joint contributions, particularly at the hip joints. The hip joints have been identified as the key determinants in allowing the varying techniques to occur. In turn, more in-depth mechanical knowledge of the differences in longswing technique may permit coaches to facilitate effective technique selection.

The last three decades of artistic gymnastics has seen prominent advances in difficulty and diversity in the skills being performed and in doing so have underpinned the rapid development of the sport (Brüggemann, 2005). The inclusion of complex skills in routines is essential in order to score highly during competition. Arkaev and Suchilin (2004) highlighted that growth in complexity can occur in two directions; athletic and coordinated. The athletic direction stems from an increase in the basic flight parameters allowing more complex shapes or rotations through flight. For example would a particular longswing technique produce the ideal trajectory to develop a pike, straight or twisting Tkachev? Flight height and rotation are paramount for the successful execution of the straddle Tkachev (Gervais and Tally, 1993) but it is unknown whether one preparatory longswing technique is more influential than any other. Coordinated complexity can be established by performing a variation of complex skills and actions within a unit of time. When applying this specifically to artistic gymnastics, gymnasts are rewarded for combinations of skills and linking them fluently with other composite elements (FIG, 2013). Therefore is it possible that a particular longswing technique allows the gymnast to

reach an advantageous position after the straddle Tkachev which then permits the gymnast to link another complex element?

Technique selection for gymnasts and coaches is complex and it is a common coaching view that gymnast height is a key determinant in the selection process for individual gymnasts (Still, 1990). In contrast however, Sheets and Hubbard (2007) later reported that coaching to a group of young gymnasts often causes variations in body size to be overlooked and therefore determining advantages of different techniques through biomechanical analyses may allow an additional analytical approach to explain why one technique could be chosen over another. Improving effectiveness in achieving the correct release parameters or facilitating the development of future skills should be key considerations in the selection process.

Borms et al. (1976) and Hiley and Yeadon (2003) highlighted that differing longswing techniques provided varying spatial and temporal characteristics at the shoulder and hip joints. Diverse movement patterns and therefore different release parameters were noted for the execution of the same final skill. The importance of the shoulders and hips in successful longswing performance has been highlighted as a key focus in previous literature (Arampatzis and Brüggemann, 1998; 1999; 2001; Irwin and Kerwin, 2005; 2007; Kerwin and Irwin, 2010; Naundorf et al., 2010). Rapid hyper-flexion to extension at the shoulders and hyper-extension to flexion at the hips has been deemed paramount for the successful execution of the longswing and have been used to define the functional phase (Irwin and Kerwin, 2005). A central focus of the current chapter is to determine the precise movement patterns employed by female gymnasts at the shoulders and hips in order to negotiate the low bar with minimal loss to the contribution from the functional phases. Quantifying the movement patterns provides more detailed knowledge and understanding of the differences in longswing technique. It has been noted that gymnasts should be in an extended position during the descent phase of the longswing when passing the low bar in order to benefit from the mechanical energetic processes of the longswing (Witten et al., 1996; Arampatzis and Brüggemann, 1999). Hiley and Yeadon (2005) showed that an early hip extension in the longswing leads to greater angular momentum and highlights the need to gain insight into the biomechanics of different longswing techniques. Maintaining an extended body position through prolonged hip extension increases the moment arm of the gymnast's weight about the bar and results in an increase in angular momentum about the bar (Williams et al., 2012).

The aim of this chapter was to investigate the underlying mechanics of distinctive longswing techniques and their effect on key release parameters. To achieve this aim the following three questions were addressed:

- How do the kinematics of the longswing preceding the straddle Tkachev alter as a function of technique?
- How do release parameters and the angular momentum about the gymnast's mass centre and the bar change as a function of longswing technique?
- How do segmental contributions to total body angular momentum differ in the three distinct longswing techniques?

Through applying a Biomechanical Conceptual Approach (Theme 2), the purpose of this chapter was to increase mechanical understanding of the three distinctive techniques that has the potential to determine which technique provides superior release parameters. New mechanical knowledge can be used to establish more systemised development pathways towards more complex skills on the uneven bars.

4.2 Method

4.2.1 Participants

Eighteen successfully executed straddle Tkachevs were selected from the qualification rounds of two International artistic gymnastics competitions: 2000 Sydney Olympic Games and the 2007 Stuttgart World Gymnastics Championships. Selected Tkachevs across the two competitions were categorised into arch, straddle and pike by their preceding longswing and the height and mass of each of the six gymnasts within each group recorded; arch (age 15.5 ± 0.8 years, height 1.47 ± 0.07 m, mass 39.0 ± 5.6 kg), straddle (age 18.8 ± 3.6 years, height 1.49 ± 0.05 m, mass 40.4 ± 6.6 kg) and pike (age 17.8 ± 1.5 years, height 1.55 ± 0.06 m, mass 45.7 ± 3.9 kg). Full gymnast profiles are reported in Appendix I.

4.2.2 Data Collection

Images of a calibration object and gymnast performances were collected from two video camcorders set at a frequency of 50 Hz. Calibration prior to the Sydney 2000 Olympic Games comprised of a three dimensional volume encompassing the uneven bars (3.2 m x 4.3 m x 3.5 m). A single calibration pole consisting of five equally-spaced (1.0 m) spheres

(0.1 m diameter) of known coordinates was sequentially placed at six pre-measured positions providing 30 known locations within the field of view. The 2007 World Championship performances were calibrated using two static (1.0 m x 1.0 m x 3.0 m) cuboids giving 48 known coordinates and a calibration volume 2.0 m x 3.7 m x 3.0 m. The origin was defined as the centre of the high bar in its neutral bar position with the calibrated volume encompassing the analysed preparatory longswing (Figure 4.1).
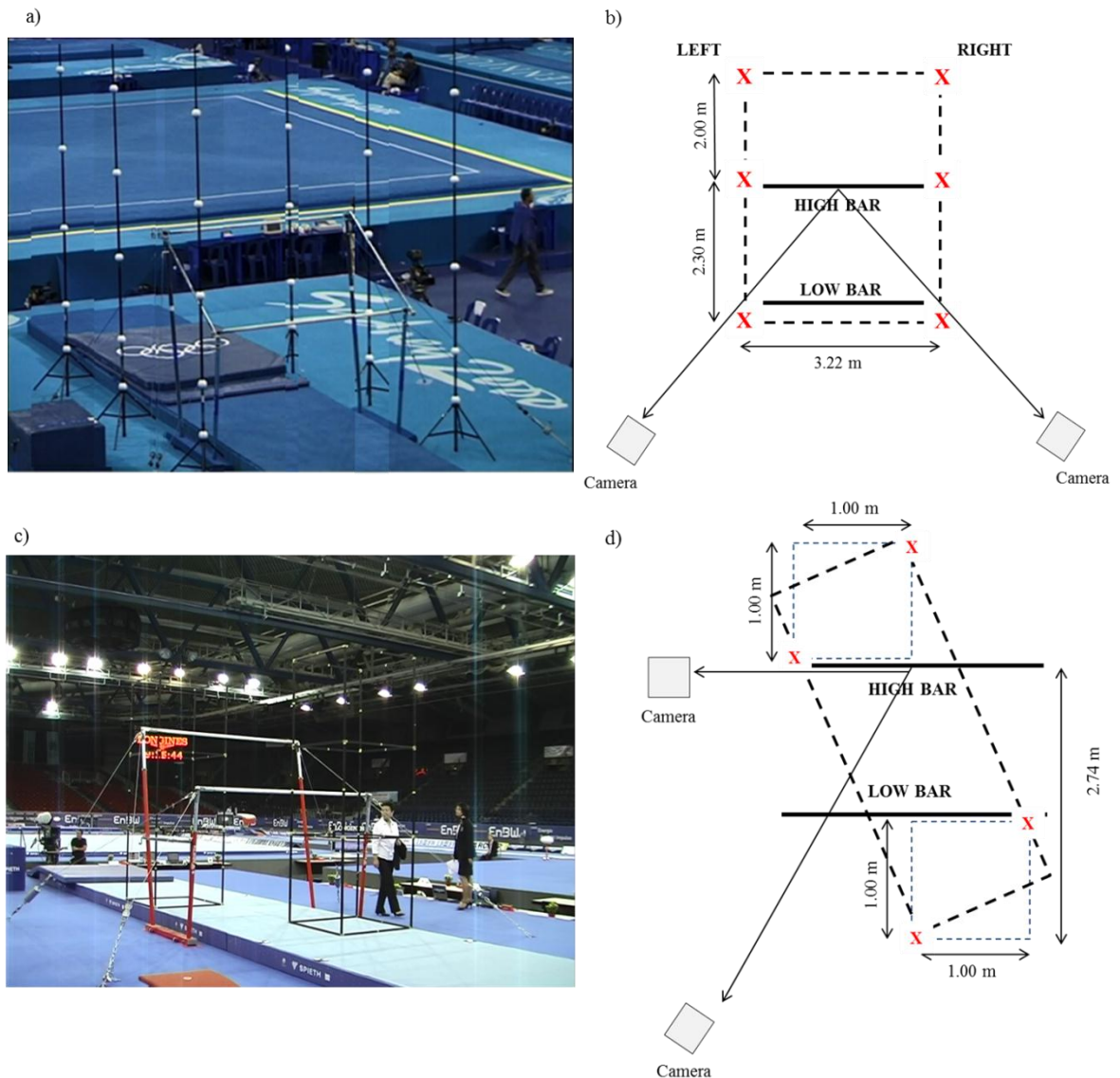
Figure 4.1. Calibration and camera set up at the 2000 Olympic Games (a and b) and 2007 World Championships (c and d). Calibration locations are defined by the red cross with the black dashed lines illustrating the calibrated volumes.

4.2.3 Data Processing

Image data were played back and cropped using Dartfish TeamPro software (Dartfish V4.5.2.0, Switzerland). Calibration and movement images were then digitised using PEAK

Motus (Vicon Peak 9.0, UK) motion analysis system for both camera views from both competitions. The digitised calibration images consisted of ten frames from each camera view that clearly showed the 30 calibration points from the Sydney 2000 arena and the 48 known points from the Stuttgart 2007 arena. Both calibration procedures were in accordance with Payton (2008) who reported six minimum known locations for 3D direct linear transformation to be successful although between 15-20 or more was recommended. The movement data comprised images of the preceding longswing, the straddle Tkachev and the re-grasp. Digitising commenced 20 frames prior to the gymnast reaching the horizontal axis illustrated as a circle angle of 180° in Figure 4.2. The established starting frame was selected due to the straddle Tkachev not always being performed after a general longswing, but often after a longswing with a twist in the longitudinal axis or even another flight element. Therefore the skill is not necessarily initiated from handstand and this starting position was decided as the appropriate point. Digitising of the movement data continued until 20 frames after the gymnast had re-grasped the high bar. Inter-digitiser reliability was established by repeated digitising of a Tkachev trial with accuracy established through the digitising of known locations within the calibration volume without including calibration points (0.017 m for a 7 m field of view).

The left and right fifth metatarsophalangeal, lateral malleolus, femoral condyle, greater trochanter, estimated centre of rotation of the glenohumeral joint, lateral epicondyle of the elbow, wrist, centre of the gymnast's head and the centre of the high bar for each movement frame were digitised from each camera view. Once exported from PEAK, the data sets from both cameras were time synchronised using the methods of Yeadon and King (1999). A 12-parameter three-dimensional (3D) direct linear transformation (Marzan and Karara, 1975) was used to reconstruct the 3D coordinate data using the TARGET high-resolution motion analysis system (Kerwin, 1995). The reconstructed 3D coordinate data were filtered with a low pass digital filter with a cut off frequency of 8 Hz based on Winter's (2009) residual analysis (Appendix II).

Customised segmental inertia parameters for each gymnast were calculated and scaled using Yeadon's (1990) inertia model, with limb lengths determined from the video data and combined with the height and mass of each gymnast. The gymnasts' centre of mass was further defined using Yeadon's mass ratio correction factor and segment centre of masses were derived from calculating the distance of the centre of mass from the proximal end of each segment. A four segment planar representation of the gymnast consisting of arms (hands, forearms and upper arms), trunk (including head and neck), thighs and shanks

(including feet) was constructed by averaging the digitised coordinate data for the left and right sides of the body.

Circle angle of the gymnast was defined from the right horizontal axis and by a vector joining the neutral bar position to the gymnast's total body mass centre. Circle angle was regarded as 90° when the gymnast was in a handstand position and continued to 450° as the gymnast returned to handstand through an anti-clockwise rotation about the bar (Figure 4.2). Data were interpolated to 101 points to allow for comparison between gymnasts; the percentage circle angle was calculated between a circle angle of 135° to release.

Figure 4.2. Dartfish™ image of the female longswing preceding the straddle Tkachev starting at a defined circle angle of 90° when the gymnast was in handstand.

The shoulder joint angle was defined by two vectors from the greater trochanter, estimated centre of rotation of the glenohumeral joint and lateral epicondyle of the elbow. The hip joint angle was defined similarly by two vectors from the femoral condyle, greater trochanter and estimated centre of rotation of the glenohumeral joint. Finally the knee joint angle was defined by two vectors from the lateral malleolus, femoral condyle and greater

trochanter. Changes in joint angles at the shoulders and hips were quantified such that shoulder extension and hip flexion were positive when the respective joint was 'closing' relative to the trunk segment. Shoulder flexion and hip extension therefore were quantified as a negative value when the joint was opening the joint angle relative to the trunk. Angular displacement data were differentiated with respect to time (CODAmotion V6.78.2; Charnwood Dynamics Ltd, Leicestershire, UK) to calculate angular velocities at the shoulder and hip joint

4.2.4 Data Analysis

Kinematic analyses consisted of locating the start and end points of the previously defined functional phases reported by Irwin and Kerwin (2005). Maximum shoulder flexion to extension and maximum hip extension to flexion were used to determine the first functional phase of the two joints. To locate the start and end points of the functional phases, the shoulder and hip angular velocity time histories were profiled. Maximum flexion and/or extension were deemed to be reached each time the respective joint angular velocity profile crossed the zero horizontal axis.

The conclusion of the preparatory longswing preceding the flight phase of the Tkachev was characterised by the gymnast performing a hyper-flexion of the shoulder and hyper-extension of the hips. Therefore, a second functional phase for the hips and shoulders was defined from maximum shoulder extension to flexion and maximum hip flexion to extension. The start and end of each functional phase for both the shoulders and hips were reported and coincided with the two extension and one flexion phases defined by Arampatzis and Brüggemann (2001). For instances where the gymnast had released the high bar prior to the conclusion of the second functional phase at the shoulders and/or hips, the gymnast's circle angle at release was recorded as the end of the functional phase.

The instant of release for the flight phase of the straddle Tkachev was determined using a linear coordinate separation between the virtual mid-wrists (average of the digitised left and right wrists) and centre of the high bar (Kerwin and Irwin, 2010). A previously conducted release sensitivity analysis concluded that a marker separation between the mid wrists and high bar 10% greater than the maximum separation throughout the preparatory longswing was the most valid value to identify that the gymnast had released the high bar. Displacement data from the flight phase were fitted quadratically for vertical motion and linearly for horizontal motion with each function being differentiated to calculate vertical and horizontal velocities of the mass centre, from which release velocities were extracted (CODAmotion V6.78.2; Charnwood Dynamics Ltd, Leicestershire, UK).

Segmental angular momentum about the gymnast's mass centre for the shank, thigh, trunk and arms were calculated using Equation 4.1. Angular momentum of the shank (L_{shank}), thigh (L_{thigh}), trunk (L_{trunk}) and arms (L_{arms}) were then summed to calculate angular momenta about the gymnast's mass centre (L_{cm}) and about the bar (L_{bar}) (Equations 4.2 and 4.3). To compare across the three longswing techniques, angular momenta about the gymnast's mass centre and about the bar were normalised by dividing by the product of 2π and the moment of inertia in a theoretical straight body position (Kerwin and Irwin, 2010), measured in straight somersaults per second (SS/s). Inertia calculations were based on scaled limb lengths from the image data and projected onto the mid-plane bisecting the real gymnast.

$$L_s = I_s \cdot \omega_s + m_s \cdot r_c^2 \cdot \omega_c$$

[4.1]

$$L_{cm} = \sum (I_s \cdot \omega_s + m_s \cdot r_c^2 \cdot \omega_c)$$

[4.2]

$$L_{bar} = \sum (I_s \cdot \omega_s + m_s \cdot r_b^2 \cdot \omega_b)$$

[4.3]

L_s = *segment angular momentum*

I_s = *segment moment of inertia*

ω_s = *segment angular velocity*

m_s = *mass of the segment*

r_c = *vector between segment mass centre and gymnast mass centre*

ω_c = *angular velocity of segment about gymnast mass centre*

L_{cm} = *angular momentum about gymnast mass centre*

L_{bar} = *angular momentum about bar*

r_b = *vector between segment mass centre and bar*

ω_b = *angular velocity of segment about bar*

The contribution of each segment's angular momentum to the total body angular momentum about the centre of mass was also reported (Equation 4.1) and analysed as compared across the three longswing techniques.

4.2.5 Statistical Analyses

Differences in discrete release parameters between the three longswing techniques were quantified using an Analysis of Variance (ANOVA). In order to meet the assumptions of the ANOVA, tests for normality (Shapiro-Wilkes) and homogeneity of variance (Levene's test) with the alpha level set to $p \leq 0.05$ were carried out. To establish the meaningfulness of differences between the three longswing techniques, effect size was also reported as a *d* score (Cohen, 1988) and interpreted using Hopkins (2002) complete scale (< 0.2 trivial, 0.2 – 0.6 small, 0.6 - 1.2 moderate, 1.2 – 2.0 large, 2.0 – 4.0 very large and > 4.0 perfect). To quantify the differences between continuous data, Root Mean Squared Difference (RMSD) and percentage RMSD (%RMSD) were determined (Equation 4.4 and 4.5). In order to calculate %RMSD, the pooled maximum and minimum values from all three longswing techniques (arch, straddle and pike) were used in calculating the dividing denominator.

$$\text{RMSD} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(x_{technique1} - x_{technique2} \right)^2}$$

[4.4]

RMSD = root mean square difference
n = number of samples
$x_{technique1}$ = data point from technique 1
$x_{technique2}$ = data point from technique 2

$$\%\text{RMSD} = \frac{\text{RMSD}}{\text{Max}_{original} - \text{Min}_{original}} \text{ x } 100$$

[4.5]

%RMSD = percentage root mean square difference
$Max_{original}$ = Maximum pooled data point
$Min_{original}$ = Minimum pooled data point

4.3 Results

In order to address the research questions of Chapter 4, the mechanical differences between the three longswing techniques were quantified and analysed at the functional phases and

release. Joint angular kinematics and key release parameters, together with angular momentum (globally around the mass centre and bar and locally at the segments) were reported.

No significant differences between the three longswing techniques in gymnast height and mass ($p \geq 0.05$) were found. However, large effect sizes for height between the arch and pike longswing were established (>1.2). With the gymnast in a fully stretched position as they circle around the high bar, calculated gymnast stretch length was also compared across the three longswing techniques. Gymnast stretch length was calculated as the sum of the four segment planar limb model (shank, thigh, trunk and arms) but revealed no significant differences or large effect size between the three techniques.

4.3.1 Functional Phase Joint Kinematics

The start of the shoulder functional phase occurred at a circle angle of 248° (±11) in the arch preparatory longswing, which was a significantly earlier ($p \leq 0.05$) circle angle (25°) than the pike longswing (Table 4.1). The change in circle angle over which the first functional phase at the shoulders occurred was greatest in the arch longswing (114°±12) compared to a smaller range for the straddle and pike (93°±26 and 93°±8 respectively). There was a 21° greater change in shoulder angle in the second shoulder functional phase for the arch longswing than the straddle longswing, which also had the smallest change in shoulder angle at 37° (±15). Shoulder extension to flexion in the second functional phase of the straddle longswing was completed over a smaller range but from a greater circle angle than the arch technique (Table 4.1), attributing to the 10% difference in the average angular velocity at the shoulders between the two longswings (Table 4.2). In addition the straddle longswing showed a significantly smaller ($p \leq 0.05$), and therefore more 'closed', shoulder angle at release.

The initiation of the hip functional phase occurred at a circle angle of 231° (±8) in the arch longswing, which was significantly earlier than for the straddle (20°) and the pike (31°). As well as each technique having a significantly different initiation of the functional phase at the hips ($p \leq 0.05$), the effect size of these differences ranged between large and perfect (1.2 - 4.0). The start of the hip functional phase was characterised by maximum extension of the hip joint, of which the arch longswing illustrated the greatest angle (-36°±8), which was 14° more extended than the pike technique. Significant differences in hip extension between the arch and pike longswing were further highlighted by a very large (2.0 – 4.0) effect size and a 31% difference in the average angle profile throughout the functional phase (Table 4.2).

Table 4.1. Mean (° [±SD]) circle angle (θC) of gymnast about the bar, changes in circle angle (ΔθC), relative joint angles (θ) and changes in joint angle (Δθ) at the start and end of shoulder and hip functional phases (FP)

	Shoulder						Hip					
	Arch (n=6)		Straddle (n=6)		Pike (n=6)		Arch (n=6)		Straddle (n=6)		Pike (n=6)		
θC_1	248*	[11]	265	[16]	273* ^{A}	[8]	231* ^{SP}	[8]	251* ^{AP}	[7]	262* ^{AS}	[4]
θC_2	362	[7]	358	[20]	366	[9]	326* ^{S}	[8]	335*	[5]	332	[3]
θC_3	401 ^{S}	[6]	409	[5]	408	[6]	398 ^{S}	[7]	409* ^{AP}	[5]	401	[3]
$\Delta\theta C_{12}$	114	[12]	93	[26]	93 ^{A}	[8]	95	[9]	85 ^{P}	[11]	71* ^{A}	[5]
$\Delta\theta C_{23}$	40	[6]	51	[17]	42	[8]	72	[7]	74	[7]	68	[5]
θ_1	-4	[9]	-4	[6]	0	[6]	-36	[8]	-35 ^{P}	[7]	-22* ^{A}	[4]
θ_2	34	[9]	37	[10]	40	[6]	53	[7]	57	[7]	52	[8]
θ_3	-24* ^{S}	[21]	1*	[12]	-12	[15]	-36	[9]	-44	[9]	-46 ^{A}	[6]
$\Delta\theta_{12}$	37	[6]	41	[8]	41	[7]	89	[14]	92 ^{P}	[13]	73 ^{A}	[9]
$\Delta\theta_{23}$	58 ^{S}	[15]	37	[15]	52	[15]	89	[11]	101	[9]	97	[6]

1 = start of FP 1, 2 = end of FP 1 and start of FP 2, 3 = end of FP 3
_denotes release prior to functional phase completion
^{A} = Arch, ^{S} = Straddle, ^{P} = Pike
Significant differences denoted by * ($p \leq 0.05$)
Large effect size (i.e. >1.2) between longswing techniques denoted by corresponding letter

The range in circle angle in which the initiation and conclusion of the first functional phase for the hips occurred was 10° greater in the arch technique than the straddle and 24° significantly greater ($p \leq 0.05$) than the pike (Table 4.1). The functional phase at the hips for the straddle longswing therefore occurred within a significantly smaller ($p \leq 0.05$) circle angle even though the straddle technique had a greater joint range to pass through. A more dynamic hip action was therefore evident during the straddle technique with a 15% greater hip angular velocity compared to the arch version (Table 4.2).

The second functional phase at the hips (maximum hip flexion to extension) initiated the reversal of rotation during the ascent of the longswing. There were no significant differences in the change in circle angle for the second hip functional phase between the three techniques ($p \geq 0.05$); however, the initiation of the functional phase was significantly earlier (9°) in the arch technique compared to the straddle.

Table 4. 2. %RMSD of key joint kinematic and normalised angular momentum (Ln) variables for each of the three distinct longswing techniques from a circle angle of 135° to release

	Arch Vs Straddle % RMSD	Arch Vs Pike % RMSD	Straddle Vs Pike % RMSD
θ_S	11.2	10.3	8.5
θ_H	17.3	31	16.1
ω_S	9.5	6.7	6.5
ω_H	15.2	17	10.3
Ln_{cm}	7.0	9.2	3.0
Ln_{bar}	20.8	21.7	2.9

4.3.2 Release Parameters

The circle angle of release for the arch longswing was significantly earlier ($p \leq 0.05$) than the straddle technique, 401° (±6) compared to 409° (±5). The remaining release parameters were similar between the three techniques with no significant differences reported ($p \geq$ 0.05). Large effect sizes for release horizontal velocity and normalised angular momenta about the gymnast's mass centre (Ln_{cm}) and bar (Ln_{bar}) were found (Table 4.3). Similarities between the straddle and pike longswings in angular momenta about the gymnast's mass centre and bar were reported with no significant differences and moderate effect sizes; a finding that was in agreement with the continuous profiles (Figure 4.3e) where less than 3%RMSD difference was observed (Table 4.2)..

Table 4.3. Mean [±SD] release parameters of varying longswing techniques preceding the straddle Tkachev

	Arch		Straddle		Pike	
θC (°)	401	[6] *SP	409	[5] A	408	[6] A
V_z (m/s)	1.51	[0.42]	1.67	[0.57]	1.73	[0.62]
V_y (m/s)	-2.20	[0.31] SP	-1.83	[0.28] A	-1.80	[0.28] A
Ln_{cm} (SS/s)	-0.53	[0.14] P	-0.44	[0.17]	-0.33	[0.16] A
Ln_{bar} (SS/s)	3.01	[0.98] P	2.18	[0.61]	2.09	[0.42] A

Ln = Normalised angular momentum, SS/s = straight somersaults per second
A = Arch, S = Straddle, P = Pike
Significant differences denoted by * ($p \leq 0.05$)
Large effect size (i.e. >1.2) between longswing techniques denoted by corresponding letter

4.3.3 Segment Angular Momentum

Table 4.4 presents the angular momentum at release for each of the four segments and the total body angular momentum about the centre of mass at release. There was no significant difference ($p \geq 0.05$) between the three longswing techniques and the amount of angular momenta each segment contributed to final angular momentum about the centre of mass.

Table 4.4. Mean [±SD] segment and total body angular momentum (SS/s) at release for the three longswing techniques preceding the straddle Tkachev

	Arch	Straddle	Pike
Ln_{shank} (SS/s)	-0.904 [0.451] [P]	-1.365 [0.568] [P]	0.020 [0.480] [AS]
Ln_{thigh} (SS/s)	-0.402 [0.179] [P]	-0.618 [0.214] [P]	-0.101 [0.210] [AS]
Ln_{trunk} (SS/s)	-0.480 [0.132] [S]	-0.344 [0.075] [A]	-0.495 [0.189]
Ln_{arms} (SS/s)	0.532 [0.218]	0.613 [0.450]	0.675 [0.420]
Ln_{cm} (SS/s)	-0.530 [0.140] [P]	-0.440 [0.170]	-0.330 [0.160] [A]

Ln = Normalised angular momentum, SS/s = straight somersaults per second
[A] = Arch, [S] = Straddle, [P] = Pike
Large effect size (i.e. >1.2) between longswing techniques denoted by corresponding letter

However, effect size calculations presented a large difference for the lower extremities (shank and thigh) and their contribution to the total body angular momentum with the pike technique contributing less than the arch and the straddle. Although there are no significant differences at release ($p \geq 0.05$), the angular momentum throughout the preceding longswings did reveal some significant differences detailed below (Table 4.5 and Figure 4.3).

Table 4.5. %RMSD of segment angular momentum contributions to the total angular momentum about the centre of mass

	Arch Vs Straddle % RMSD	Arch Vs Pike % RMSD	Straddle Vs Pike % RMSD
Ln_{shank}	11.8	15.6	6.0
Ln_{thigh}	10.4	13.9	6.2
Ln_{trunk}	6.3	5.1	4.3
Ln_{arms}	10.2	9.2	6.8
Ln_{cm}	7.1	9.2	4.5

The angular momentum contribution of the shank and thigh segments to total angular momentum about the mass centre for the arch longswing was over 10% different (Table 4.5) than the straddle and pike throughout the preparatory longswing (135° to release) . Figure 4.3 illustrates this difference and can be seen in the early stages of the longswing before peak angular momentum is generated (around 50-60% of the circle angle). However, once the angular momentum is reversed and is decreasing, the segment contribution for each of the three techniques is very similar (Figure 4.3). The one exception is the arm segment for the arch technique that would explain the higher %RMSD of around 10%.
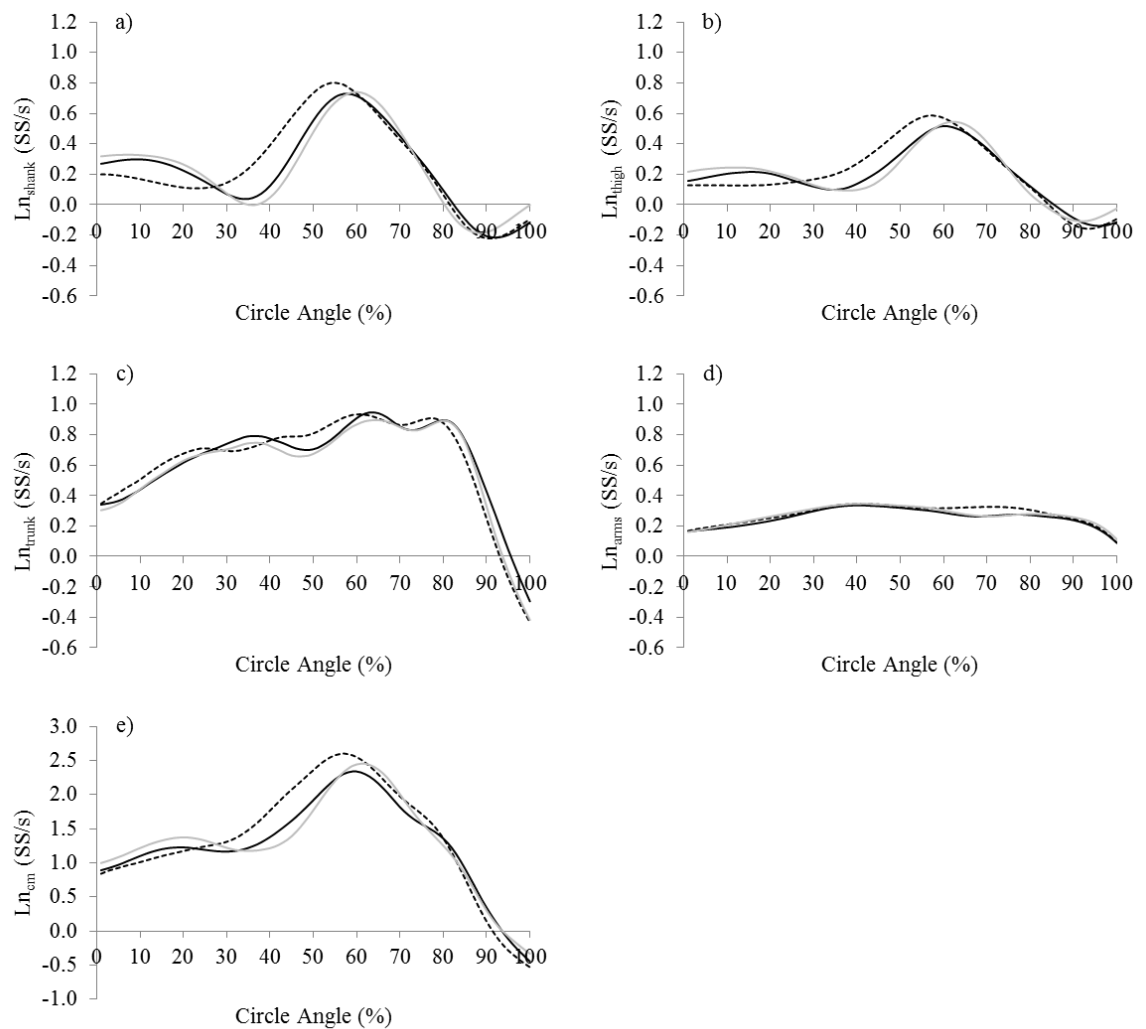
Figure 4.3. Segment angular momenta (a-d) and total angular momentum about the centre of mass (e) for the arch (dashed), straddle (black) and pike (grey) preceding longswings.

The significant differences ($p \leq 0.05$) in segment angular momentum occur when observing the time at which minimum and maximum angular momentum is generated and

therefore the change in rotation. There is a significant difference in angular momentum at the shank segment between the straddle and pike techniques when the angular momentum of the shank is at its lowest ($p \leq 0.05$). This occurs at 92% of the circle angle for the straddle and 88% for the pike. When observing the contribution of the thigh segment, the time at which maximum angular momentum is generated throughout the preceding longswing is significantly earlier in the arch longswing than the pike (57% of the circle angle compared to 63%). As well as the circle angle at which the lower extremities of the pike longswing reach maximum and minimum angular momentum, the change in circle angle in which the change in angular momentum occurs from maximum to minimum is also significantly shorter than the other two techniques. This occurs on the upswing of the preceding longswing and the change in shank and thigh angular momentum occurs over a much smaller circle angle.

4.4 Discussion

The aim of this chapter was to gain insight into the mechanics of three distinctive longswing techniques and the influence of their varying movement patterns on the kinematics and angular momentum of the preparatory longswing. This section discusses how the greater mechanical understanding of the preceding longswing may enhance the process of technique selection through increased knowledge of how the joint kinematics, consequent release parameters and segment contributions alter as a function of longswing technique.

A traditional coaching view in Women's Artistic Gymnastics is that technique selection is based on gymnast height (Still, 1990); specifically, taller gymnasts select the pike and straddle techniques whilst it is believed that shorter gymnasts select the arch technique. The initial results from this chapter however found no statistically significant differences in gymnast's height between the three longswing techniques. However, a large effect size in gymnast height between the pike and arch longswing do support the premise that gymnast height may be one of the contributing factors determining the longswing technique selection process, although this was found not to be the case for the straddle longswing in this chapter. Furthermore, an investigation into gymnast-length (summation of segment lengths from gymnast's wrists to toes) reported no significant differences or large effect sizes between the three techniques.

With gymnast height and length not being the sole contributing factors to the selection of techniques, establishing mechanical variations in the key characteristics highlighted potential advantages of one longswing technique over another. This quantitative knowledge could provide coaches with meaningful information to allow objective decisions to be made regarding technique selection, facilitating the coaching process and making training more effective.

In comparison to the straddle and pike variants, the arch longswing was identified as deviating furthest from the other two techniques in terms of functional phase location and joint angular kinematics. The functional phases underpin the successful performance of the longswing. The hyper-extended body configuration during the arch longswing enabled the functional phases to be started at a significantly earlier circle angle compared to the straddle and pike variants. A significantly earlier hip functional phase for the arch longswing enabled the gymnast to reach a greater degree of hip extension. This chapter was supported by previous research that identified that an earlier hip extension leads to greater angular momentum in the longswing (Hiley and Yeadon, 2005) and is supported by the findings in this chapter (Table 4.2 and 4.3) with a sustained period of full body extension increasing the moment arm about the bar.

When performing the pike longswing a delayed hip extension as well as a restricted angle range delayed the initiation of the first hip functional phase. The constrained movement pattern restricted the functional phase which according to Yeadon and Hiley (2000) has the potential to limit energetic inputs from the gymnast to the gymnast-high bar system. The potential of the gymnast to utilise energetic processes has been shown to be important for generating angular momentum at release (Arampatzis and Brüggemann, 2001; Kerwin and Irwin, 2010). The flexed body configuration of the pike longswing may contribute to the pike longswing having a large effect size for angular momentum about the mass centre when compared to the arch. Insight into joint angular kinematics has therefore provided coaches with vision into the influence that functional phase location has on the generation of angular momentum.

The straddle Tkachev is interesting within biomechanical research due to the requirement of the gymnast to change the direction of angular momentum about the mass centre during their preparatory longswing (Naundorf et al., 2012). The significantly earlier initiation of the second hip functional phase in the arch longswing may be beneficial in facilitating this reversal of angular momentum when approaching release, potentially explaining release angular momentum values at the high end of the range compared to the other techniques.

The hip extension prior to release is supported by findings of Arampatzis and Brüggemann (1999) and allows the transfer of forward rotation from the lower limbs to the whole body (Fink, 1988).

With the exception of the angle of release between the arch and straddle techniques, no statistically significant differences were found in the key release parameters examined in this investigation between the three longswing techniques. Therefore the significant differences in joint angular kinematics prior to release in the longswing do not appear to influence the flight phase. The three techniques appear to be similarly effective due to the successful completion of the desired skill but have been classified with mechanical differences. Effect size calculations did reveal a 'large effect' for three of the key release parameters between the arch and the pike longswing; horizontal velocity, normalised angular momentum about the gymnast's mass centre and normalised angular momentum about the bar. Effect size results provide further insight into the differences between these techniques, particularly as purposeful sampling was employed. Small samples are a common theme in research when examining elite performers and benefits in terms of ecological validity (Elliott et al., 2006) may adversely affect the identification of differences, type II errors (Mullineaux et al., 2001).

The significantly earlier angle of release during the arch longswing technique may be explained by the greater shoulder flexion (more opened shoulder angle) at the point of release. A large shoulder angle at release was also identified by Arampatzis and Brüggemann (2001) and stated that greater shoulder flexion was the product of muscular energy produced by the gymnast at the final stage of the longswing. Issues surrounding the musculoskeletal work at the shoulder have been highlighted previously and potentially could provide insight into the role of the shoulder joints preceding the straddle Tkachev. Future research examining joint kinetic differences between the three longswing techniques regarding musculoskeletal demand at the shoulders would be useful and timely and may be supported by Kerwin and Irwin (2010) who highlighted differences in shoulder kinetics between two versions of the female Tkachev.

The more open shoulder configuration could be due to gymnasts actively 'pressing' on the bar prior to release suggesting a difference in gymnast interaction with the bar between techniques. With a further kinetic analysis this may be clarified along with any other actions that may be made possible by a particular longswing technique. The subsequent body configurations at release may explain the general trend of an increase in horizontal velocity and angular momentum and reduction in vertical velocity across the three

techniques. With the arch longswing providing the gymnast with greater horizontal velocity travelling across the bar, this may place the gymnast in a favourable position to continue with more complex skills linking on from the straddle Tkachev. Clearing the bar quicker with a smoother trajectory allows the initiation of the following longswing to be earlier and the preparation for the following skill to be more efficient.

Meaningful differences were established in release angular momentum about the gymnast's mass centre and bar with significant differences in key joint angular kinematics. When observing the segment contribution to total body angular momentum it was clear that the lower limbs played a dominant role as expected and was supported by Brüggemann et al. (1994). The shank and thigh segments in the arch longswing contributed earlier and greater to total body angular momentum than the other two techniques, which may be explained by a subsequent joint kinetic analysis that could provide insight into the musculoskeletal demands of each technique.

The current chapter has shown significant differences between the functional phase characteristics of the three longswing techniques. Differences were not reflected in the release characteristics and therefore no significant advantages in performing one technique over another were identified. However, variations of specific movement patterns utilised when performing the varying longswing techniques in order to achieve the same release parameters may imply the need for specific physical preparation within the coaching process (Irwin et al., 2005). Large effect sizes between release characteristics suggest that purposeful sampling may have affected these findings; therefore, future studies using an increased sample size and trial number would be beneficial. Furthermore, looking forward to Chapter 5 and Chapter 6, a more extensive analysis into the joint kinetics of these three techniques may provide an idea of whether a particular technique and the movement patterns involved are more demanding than the comparative techniques.

4.5 Conclusion

This chapter aimed to gain further insight into the underlying mechanics of various longswing techniques used for the execution of the same final skill, the straddle Tkachev. Joint angular kinematics varied between the three longswing techniques with the arch longswing initiating the shoulder and hip functional phases significantly earlier with significantly greater hip extension. With the exception of release angle for the arch technique, there were no significant differences in release parameters; however the arch

technique had meaningful differences with increased horizontal velocity and normalised angular momenta. Large effect sizes in angular momentum in the pike longswing were contributed by the lower contribution of the thigh and shank to total angular momentum.

The key implication of Theme 2: Biomechanical Conceptual Approach was to further develop knowledge of the varying longswing techniques to explain the differences in angular position of the gymnast within the circle angle and the magnitude and distribution of joint kinematics with regard to the shoulder and hip functional phases. A joint kinetic analysis will determine the work requirement to perform the longswing techniques effectively as well as the demand placed on the gymnast; facilitating the technique selection process of the coach. In order to apply the kinetic analyses to elite competition data, Theme 3: Method Validation will aim to validate the inputs to an inverse dynamics analysis within the field which will then drive the analysis of the subsequent chapter.

CHAPTER FIVE

EVALUATION OF JOINT KINETIC CALCULATIONS DURING THE FEMALE LONGSWING PRECEDING THE STRADDLE TKACHEV

5.1 Introduction

Chapter 4 aimed to investigate the influence of longswing technique on the key kinematics and release parameters of the straddle Tkachev. Significant differences in the angular position and joint angles during the varying techniques were combined with similarities in the release parameters; advantages were therefore not apparent as to why one technique may be selected over another. Further investigation is required into the physical demands of each technique and therefore the joint kinetics. Joint kinetics may provide reasoning into why one gymnast selects a certain technique over another based on the musculoskeletal dynamics of the skill that generates differences in the movement patterns; this would have particular implications for skill development and physical preparation.

Joint kinetic analyses in high bar and uneven bar research have previously been investigated using both forward dynamics (Arampatzis and Brüggemann, 1998; Yeadon and Hiley, 2000) and inverse dynamics (Gervais, 1993; Kerwin and Irwin, 2010). The requirement of known external forces, kinematic data and individual body segment inertia parameters (Figure 5.1) of the segments concerned over the input of internal joint forces of a full body model has often permitted inverse dynamics (IDA) to be the more favoured method of approach (Winter, 2009). The occurrence of estimation errors is more likely in the full body model required in forward dynamics highlighting the paramount importance of a valid replication of the entire body (Winter, 2009).

In order to input known force data into IDA calculations there have previously been a number of direct and indirect methods employed. Direct methods have utilised the use of an instrumented high bar (Kopp and Reid, 1980; Ishi and Komatsu, 1987; Arampatzis and Brüggemann, 1998; 1999; 2001; Hiley et al., 1999) whereas indirect methods have used positional (Gervais, 1993) and displacement data (Kerwin and Hiley, 2003; Kerwin and Irwin, 2006) to predict the external force at the bar as well as the assumption of zero forces at the toes as an external force input to IDA (Kerwin and Irwin, 2010). Prior to the work of Kopp and Reid (1980) bar force data had not been utilised by top level coaches and gymnasts and to the best of the author's knowledge, data from elite competition had been

kinematic in nature, omitting knowledge of key musculoskeletal characteristics and potential demands of high bar performances.

The use of bar displacement combined with the requirement of kinematic input introduces the different methods of collating kinematic data. Traditionally in gymnastics research, manual digitising has been the method of data collection with the derived coordinates reconstructed to provide coordinate data. Figure 5.1 illustrates the more contemporary alternative of automated motion analysis systems within a controlled lab environment that can be used to obtain kinematic information.
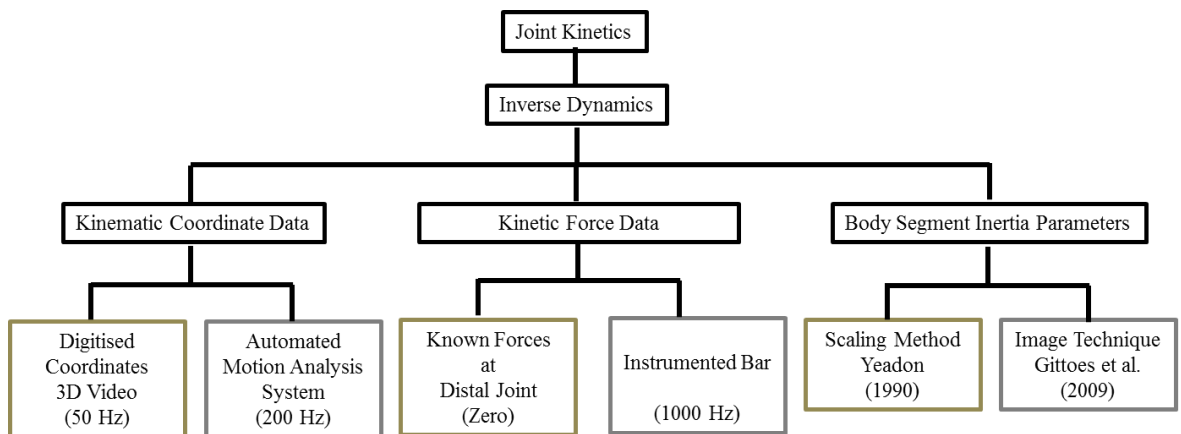
Figure 5.1. Schematic model for inputs to joint kinetic calculations illustrating both the **field** and **lab** based methods of approach.

When working within elite competition, direct methods are difficult to organise and employ due to the impediment of markers and wires to the equipment and performer for example. Indirect methods to obtain body segment inertia parameters, kinematic and kinetic inputs therefore need to be applied. Traditionally in the field of gymnastics and more specifically swinging biomechanics, the unobtrusive methods are conducted over the lab based procedures (Figure 5.1). Since the kinetic research of Kopp and Reid in 1980, Arampatzis and Brüggemann (1999; 2001) are the only authors to the best of the author's knowledge to collect and publish data using an instrumented bar in an elite competition (1994 World Championships) highlighting the dominance of indirect methods.

Challis and Kerwin (1996) declared that analyses into the joint moments of an athlete lead to a greater understanding of the roles played by that athlete's muscle groups. In conjunction with the assumptions made to conduct a joint moment analysis through inverse dynamics, a number of errors are also reported by the above authors. Challis and Kerwin (1996) also established that errors linked to the motion and force measurement system

were eliminated due to the calibration procedure and fact that the distal rigid body is in free space and therefore a known force of zero. Errors contributed by the body segment inertia parameters, estimation of joint centres and measurement of positional data were of higher influence. Thorough error estimation is required to provide detailed information on data accuracy (Schwameder, 2008).

Elliott and Alderson (2006) emphasised the need for ecological validity to feature strongly in sports biomechanics research and later further highlighted the need for simulated field conditions in order to investigate reliability and validity in the lab and field (Elliott and Alderson, 2007). An evaluation of indirect methods is yet to be reported against the directly measured methods in a pseudo competition set up for the women's uneven bars. The aim of this chapter was to investigate the errors associated with inverse dynamics and to validate field based measures against their lab counterparts in the calculation of joint kinetics on the uneven bars. To achieve this aim the following research questions were addressed:

- What is the influence of changes in the input parameters on an inverse dynamics analysis and the consequent joint kinetics?
- How do predicted bar forces, joint moments, joint powers and joint work calculated indirectly from field based measurements differ from those from lab based measurements?
- What level of confidence can be had in mechanical findings that utilise indirect methods of approach?

Through Method Validation (Theme 3) the overall purpose of this chapter was to gain knowledge and understanding of the errors associated with employing an inverse dynamics analysis in the field, in preparation for minimising error when calculating joint kinetics in the subsequent chapter.

5.2 Method

This chapter combined two methodological approaches (field and lab) that share the same collection procedure but diverge when reaching the data processing protocol. The field (3D video data) processing was detailed earlier in Chapter 4 section 4.2.3 and therefore only summarised with the lab based processing reported here. Throughout the chapter the field has been defined as the competition environment and the lab as a controlled environment.

5.2.1 Participants

One International female gymnast (age 15.9 years, height 155 cm, mass 59.6 kg) performed three sets of five longswings and five Tkachevs. Attire consisted of a short sleeved leotard with training shorts and informed consent was collected from both the gymnast and their national coach. Ethical approval was confirmed by the Cardiff Metropolitan University School Ethics Committee prior to the onset of the data collection.

5.2.2 Data Collection

Two video cameras (Sony HVR-Z1E, Japan) were positioned 51.7 m and 42.9 m to the left and right of the performance area respectively with the optical axes of the cameras intersecting at an angle of 68° (Figure 5.2).
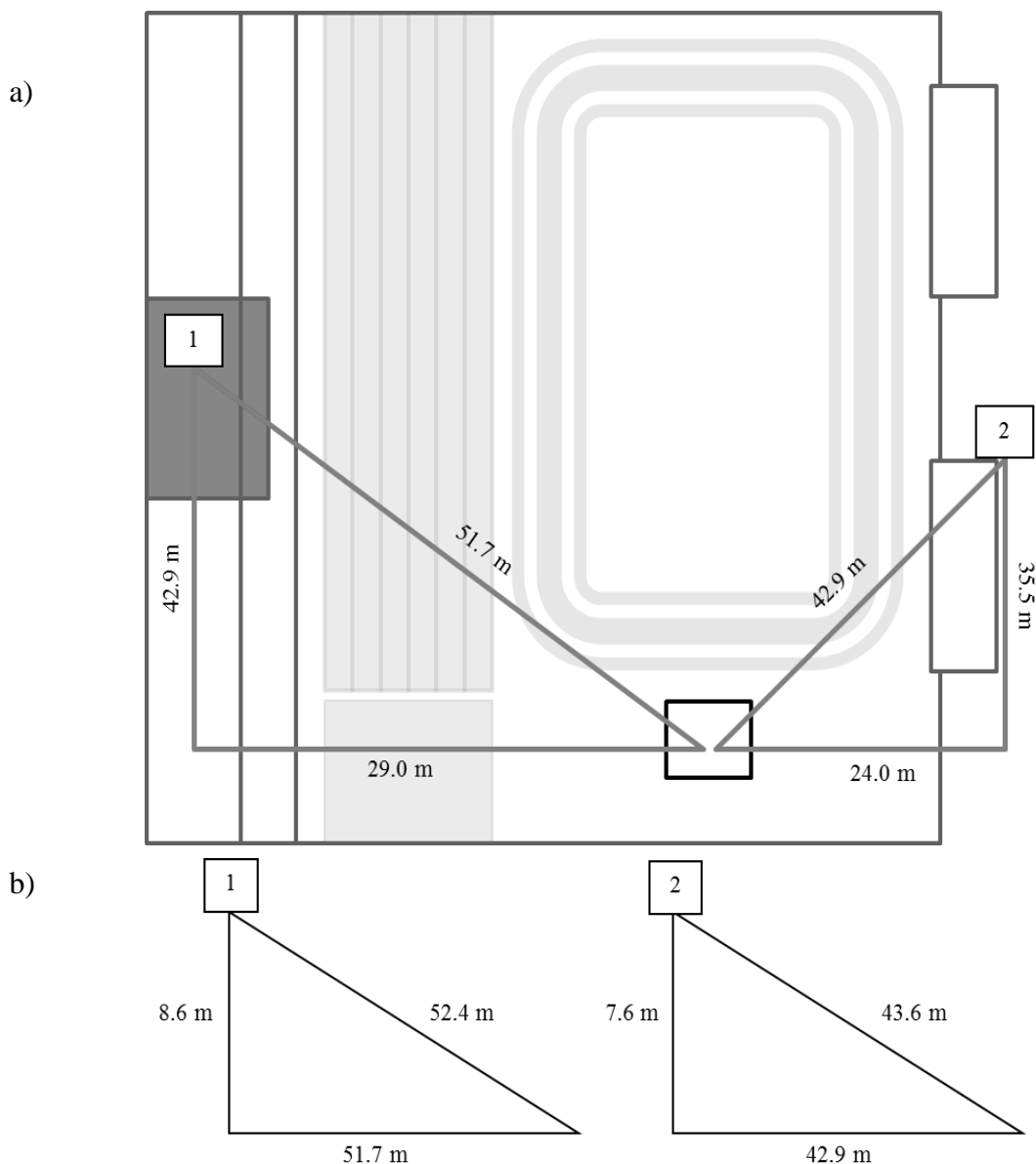
Figure 5.2. 50 Hz camera set up [1] and [2] in relation to the high bar from an overhead (a) and cross sectional (b) field of view.

Camera one to the left was positioned 8.6 m high with camera two positioned at a height of 7.6 m. Each camera had a tilt angle of 7° to the centre of high bar. Each camera captured images at 50 Hz which produced the field based measure to coincide with a competition environment, with a shutter speed set to 1/300. A calibration pole with five spheres located approximately 1 m apart was positioned around the performance area providing calibrated volume 3.5 x 2.0 x 4.0 m (Figure 5.3).

Four CODA CX1 scanners (CODAmotion, Charnwood Dynamics Ltd, Leicester, UK) scanners were positioned in an approximate rectangle, 3.7 m x 6.2 m, each directed towards the centre of the high bar (Figure 5.4). A field of view exceeding 2.5 m around the centre of the high bar was permitted. The motion analysis system was aligned with the origin located directly beneath the centre of the high bar through a plumb line. To determine the x axis a separate CODA marker was positioned directly beneath the high bar approximately 0.50 m to the right by the same method of a plumb line. The y axis was finally defined by placing a marker perpendicular to the origin approximately 0.80 m in front allowing the z axis to define the vertical axis. CODA was set to a sampling rate of 200 Hz and captured markers 1 − 16 on each of the participants and 17 − 20 on the apparatus.
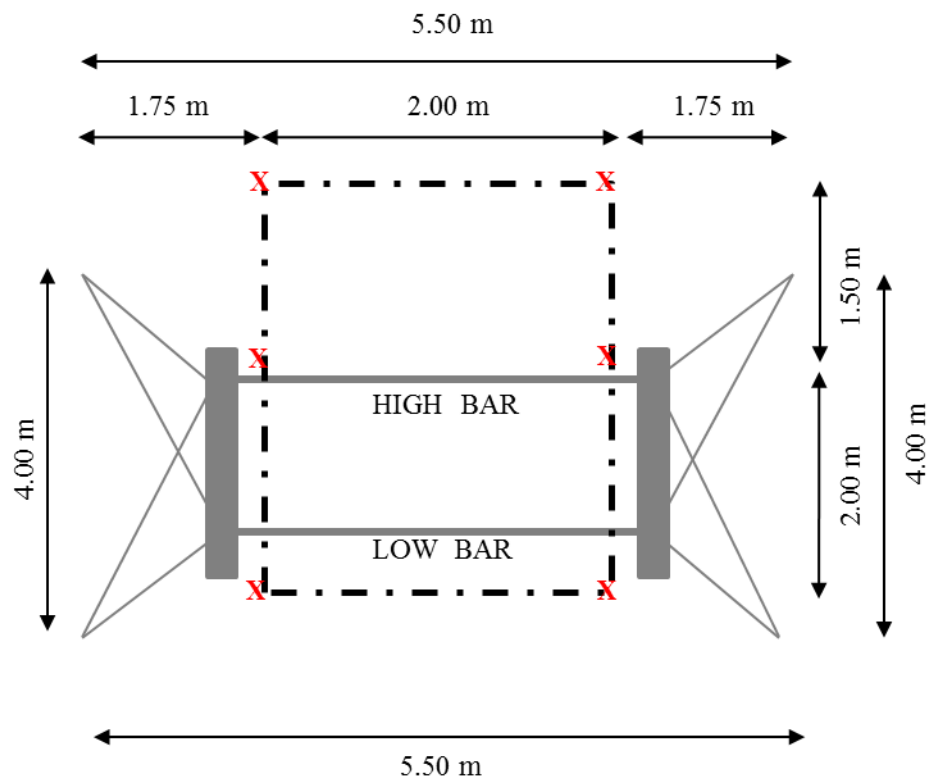
Figure 5.3. 3D Calibration set up with X marking the known calibration locations.

The instrumented high bar collected force data at a frequency of 1000 Hz. Voltage data were collected from strain gauges located on the left and right hand side of the bar and recorded both vertical and horizontal loads. Net vertical and horizontal voltages were then calculated and permitted loading at any point along the high bar to be recorded. Prior to data collection, vertical and horizontal forces were calibrated by loading and unloading the high bar with increments of known loads (0 – 2000 N) both vertically and horizontally. Similarly to Kerwin and Hiley's (2003) lab based calibration, a tension balance system was employed to the high bar. Cagran et al. (2010) reported advantages of this calibration approach over the more traditional hanging of weights as being a) the application of large forces b) the avoidance of errors due to friction and c) avoidance of oscillation when adding additional weights. Bar displacement data (mm) obtained from the centre high bar CODA marker, known calibration loads (N) and vertical and horizontal voltages (mV) were recorded for a 5 s period.

An array of 20 light-emitting-diodes (LED) was positioned in the field of view of the 50 Hz 3D camera set up. The LED array (Nakedeye Technology, Bath, UK) allowed synchronisation between the force and video data by illuminating at 1-ms intervals once triggered remotely.
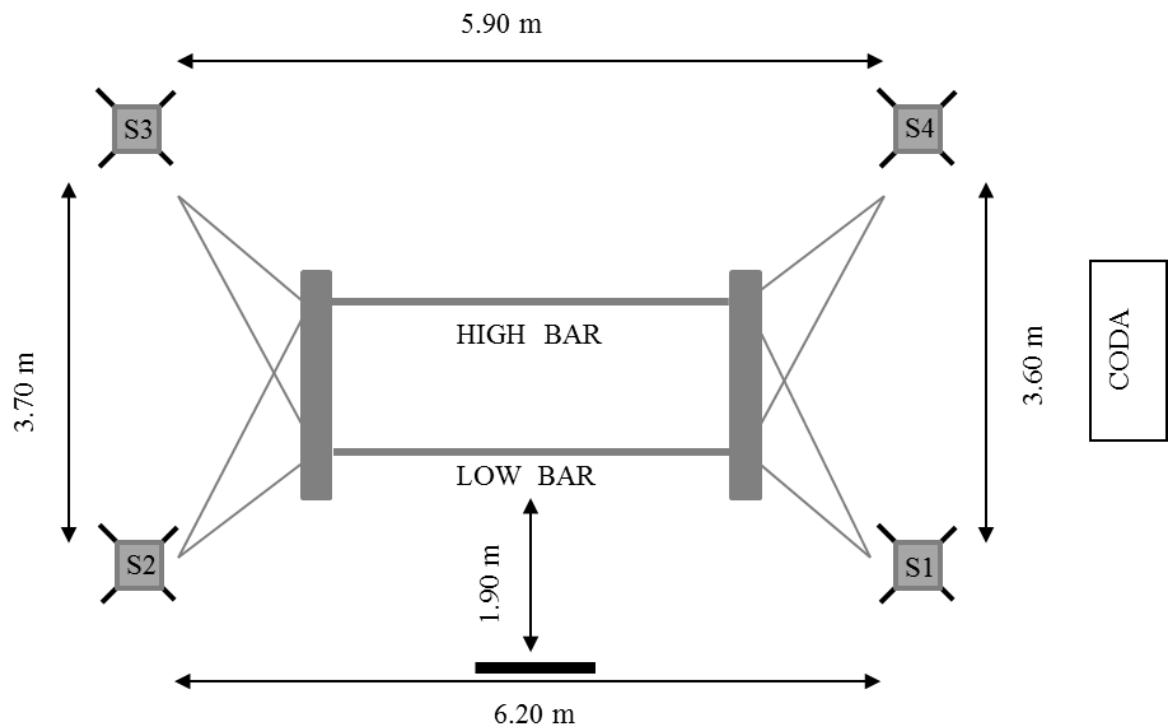
Figure 5.4. CODA, Scanner (S1, 2, 3, 4) and LED (-) set up.

CODA markers were positioned on the gymnasts' joint centres on the left and right fifth metatarsophalangeal, lateral malleolus, femoral condyle, greater trochanter, estimated centre of rotation of the glenohumeral joint, lateral epicondyle of the elbow, mid ulna and wrist (wrist markers were removed after the static trial in order for the gymnasts' guards to be tightened sufficiently). Markers were also located on the underside of the high bar at the centre of the high bar (1.20 m) and 0.60 m from the left and right end of the bar (Figure 5.5).

Joint coordinate data were first collected for a static trial where the gymnast stood beneath the high bar, feet shoulders width apart and with their forearm perpendicular to their upper arm. This enabled a virtual marker of the wrist to be created using the wrist, mid ulna and lateral epicondyle of the elbow markers. Following the 5 s static trial, the wrist marker was removed to allow the tightening of the gymnast's hand guards and the gymnast conducted a 5 minute warm up on the uneven bars.

Gymnast height and mass were collected post data collection once all active markers were removed. Body mass was measured using laboratory weighing scales (Seca, Hamburg, Germany) and gymnast height by the laboratory stadiometer (Holtain Ltd, Pembrokeshire, UK). Images were recorded based on Gittoes et al. (2009) image technique using a digital SLR camera (Canon EOS 400D, Japan) for the gymnast's individual body segment inertia parameters obtained in the lab.

1	Left MTP	9	Right MTP
2	Left Ankle	10	Right Ankle
3	Left Knee	11	Right Knee
4	Left Hip	12	Right Hip
5	Left Shoulder	13	Right Shoulder
6	Left Elbow	14	Right Elbow
7	Left Forearm	15	Right Forearm
8	Left Wrist	16	Right Wrist
		17	Left Bar
		18	Centre Bar
		19	Right Bar
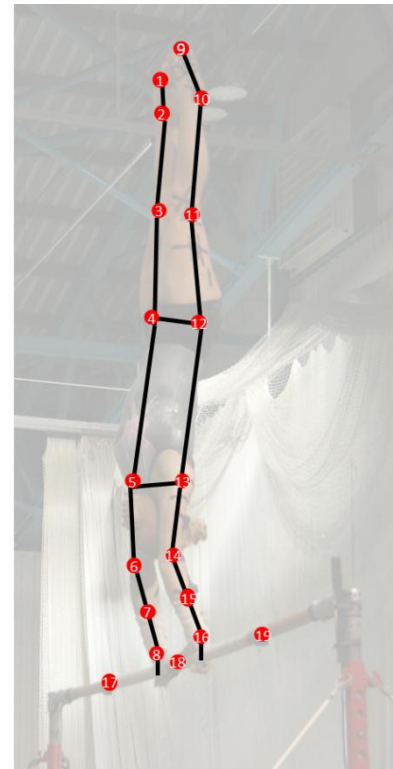
Figure 5.5. Joint centre marker positions and high bar marker positions.

5.2.3 Data Processing

5.2.3.1 Lab Protocol: Automated Motion Analysis

For both the general longswing and the longswing preceding the straddle Tkachev, bilateral symmetry was assumed (Irwin and Kerwin, 2001) and a four segment planar representation of the gymnast produced. The representation model consisting of arm (hands, forearms and upper arms), trunk (including head and neck), thigh and shank (including feet) segments was constructed by averaging the raw coordinate data for the left and right sides of the body.

Coordinate data were filtered using a Butterworth low-pass digital filter set to a cut of frequency of 6 Hz based on a Winter's residual analysis (Winter, 2009). Residuals were calculated from 0 Hz to 30 Hz for the horizontal and vertical locations of the joint centres.

The gymnasts' centre of mass was defined similarly to the field protocol (3D video data) using Yeadon (1990) geometric model. Gymnast limb length, height and mass were combined with Yeadon's mass ratio correction factor. Segment centre of mass were derived from calculating the distance of the centre of mass from the proximal end of each segment.

Circle angle of the gymnast was defined by employing a vector from the right horizontal axis joining the neutral bar position to the gymnast's centre of mass. Circle angle was regarded similarly as 90° when the gymnast was in a handstand position and continued to 450° as the gymnast returned to handstand through an anti-clockwise rotation about the bar

5.2.3.2 Field Protocol: 3D Video

Calibration and movement images were digitised using PEAK Motus (Vicon Peak 9.0, UK) motion analysis system for both camera views. Ten frames of the calibration image were digitised and from handstand position to subsequent handstand position above the bar or 20 frames post release for the longswing movement images, both general and preceding the straddle Tkachev respectively.

Similarly to the kinematic analyses in Chapter 4, the left and right fifth metatarsophalangeal, lateral malleolus, femoral condyle, greater trochanter, estimated centre of rotation of the glenohumeral joint, lateral epicondyle of the elbow, wrist and centre of the gymnast's head were digitised. Once exported from PEAK, a 12-parameter three-dimensional direct linear transformation (Marzan & Karara, 1975) was used to reconstruct the coordinate data using the TARGET high-resolution motion analysis system

(Kerwin, 1995). The data sets from each camera view were time synchronised using the methods of Yeadon and King (1999).

The same procedure of a residual analysis for filtering the data (Winter, 2009), calculating body segment inertia parameters and defining circle angle were then employed as above in section 5.2.3.1. A cut of frequency of 6 Hz was also established for the field data.

5.2.4 Data Analysis

5.2.4.1 Inverse Dynamics Analysis

All data analysis was performed utilising a customised Mathcad program (Kerwin, 2013. MathCad14, Parametric Technology Corporation, USA). Each of the four segments in the planar representation of the gymnast were assumed to be rigid with uniform density and connected via hinge joints. A two dimensional inverse dynamic analysis (IDA) was then performed in order to calculate the internal joint forces at the knees, hips, shoulders and high bar. Zero external forces were known at the toes (Gervais, 1993) and by applying Newton's 2nd law of linear motion (Equation 5.1) net joint forces were calculated from the gymnast's toes up to the high bar utilising the field kinematic data.

$$\sum F = m \cdot a$$

[5.1]

F = linear force acting on segment
m = mass of segment
a = linear acceleration of segment

Figure 5.6 below illustrates the forces acting on the ith segment in both the horizontal (y) and vertical (z) direction as a free body diagram. Net linear forces acting at each joint were calculated from the mass and acceleration of each segment and the force transferred from the preceding segment (Equation 5.2 and 5.3).
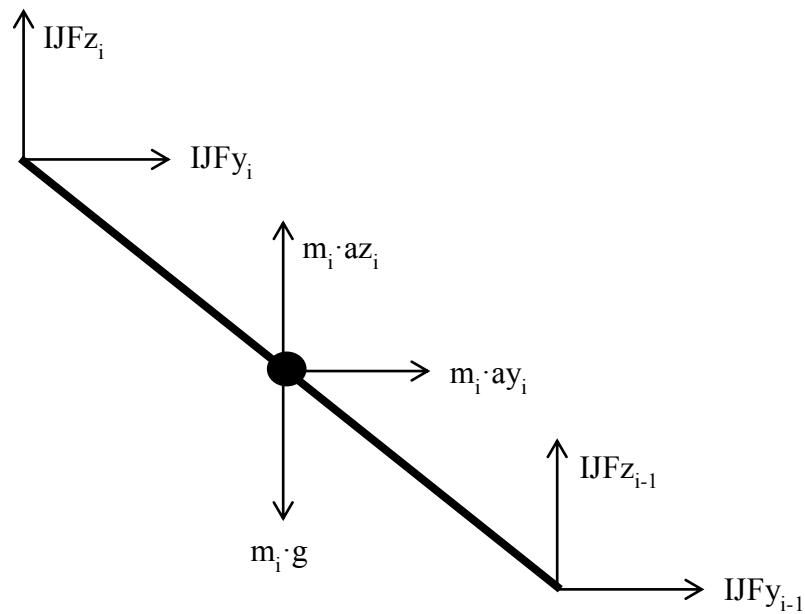
Figure 5.6. Free body diagram to illustrate the forces acting on the ith segment.

$$IJFy_i = m_i \cdot ay_i - IJFy_{i-1} \qquad [5.2]$$

IJFy = horizontal internal joint force

ay = horizontal acceleration of segment

i = ith segment

$$IJFz_i = m_i \cdot az_i - IJFz_{i-1} - m_i \cdot g \qquad [5.3]$$

IJFz = vertical internal joint force

az = vertical acceleration of segment

g = acceleration due to gravity

Joint moments were calculated using Newton's second law of angular motion (Equation 5.4) stating that the sum of moments about the segments centre of mass is equal to the segments rate of change in angular momentum. Equation 5.4 expanded and with the aid of Figure 5.7 reveals the Equation 5.5 used for the calculation of joint moments at the shoulder, hip and knee.

$$\sum JM_i = I_i \cdot \alpha_i$$

$$[5.4]$$

JM = net joint moment

I = moment of inertia

α = angular acceleration of segment

i = i^{th} segment

$$JM_i = (IJFz_i \cdot pro_y) + (IJFy_i \cdot pro_z) + (IJFz_{i-1} \cdot dis_y) + (IJFy_{i-1} \cdot dis_z) + I_i \cdot \alpha_i - JM_{i-1}$$

[5.5]

IJF = internal joint forces

y = horizontal direction

z = vertical direction

pro = distance between the CM and the proximal end of the segment

dis = distance between the CM and the distal end of the segment

Figure 5.7 illustrates the internal joint forces acting at a known distance from the segment centre of mass and the resultant joint moment, including the angular acceleration. The joint centre coordinates and mass centre location, although not illustrated, were included in the calculation of distance between the segment centre of mass and distal end of the segment (dis_y, dis_z) and the proximal end of the segment (pro_y and pro_z).
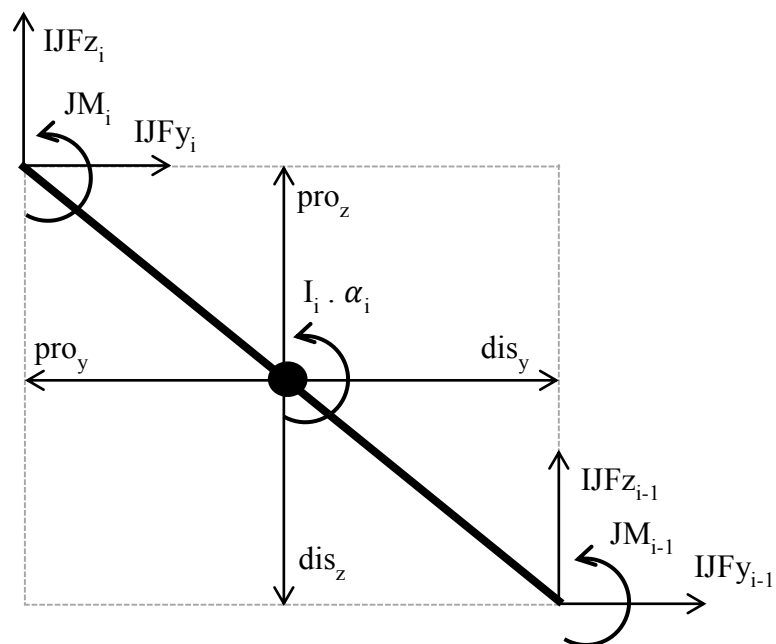
Figure 5.7. Free body diagram to illustrate the joint moments acting on the ith segment, vertical and horizontal internal joint force and the distance at which these forces act.

Shoulder, hip and knee joint powers were calculated as the product of the previously defined joint moment and angular velocity (Equation 5.6).

$$JP_i = JM_i \cdot \omega_i \qquad [5.6]$$

JP = net joint power
JM = net joint moment
ω = joint angular velocity
i = i^{th} segment

Shoulder, hip and knee joint work were calculated using Equation 5.7 below, as the time integral of joint power.

$$JW_i = \int_{t1}^{t2} JP_i \cdot dt$$

$$[5.7]$$

JW = net joint work
JP = net joint power
t = time

5.2.4.2 Sensitivity Analysis

A sensitivity analysis was employed to the field based data (3D video) to investigate the errors associated with inputs to an inverse dynamics analysis. This approach was in accordance to the errors reported by Challis and Kerwin (1996) and the influence on the subsequent joint kinetic analyses. Inputs to IDA (kinematics and BSIP) were perturbed around the original inputs and differences between the original data and perturbed data in the calculation of joint moments, powers and work were reported. The differences obtained were quantified by calculating the root mean squared difference (RMSD) (Equation 5.8) during the full longswing (circle angle of 135° to 450° for the longswing trials and 135° to release for the Tkachev trials). RMSD values were further divided by the range of the original measured output in order to obtain relative differences across trials (Equation 5.9).

$$RMSD = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_{original} - x_{perturbed}\right)^2}$$

[5.8]

RMSD = root mean square difference

n = number of samples

$x_{original}$ = original data point

$x_{perturbed}$ = perturbed data point

$$\%RMSD = \frac{RMSD}{Max_{original} - Min_{original}} \times 100$$

[5.9]

%RMSD = percentage root mean square difference

$Max_{original}$ = Maximum original data point

$Min_{original}$ = Minimum original data point

Sensitivity Analysis of Kinematics

To obtain the most appropriate cut off frequency Winter (2009) recommended the use of a residual analysis on the difference between filtered and unfiltered signals over a wide range of cut off frequencies. A 6 Hz Butterworth filter was employed and following the work of Kerwin and Irwin (2006) the cut of frequency altered. Cut off frequencies of 2.5 Hz, 5 Hz, 7.5 Hz and 10 Hz were selected as outside of this range the data were either over filtered or too little noise was removed. Predicted bar forces and shoulder, hip and knee joint moments, powers and work were then compared through the RMSD and %RMSD between filtering at 6 Hz and the four other selected cut off frequencies.

Joint centre locations derived from the field comprise of random error that can occur by the human error present in manual digitising; which are then reflected in the reconstructed coordinates of the joint centres. To investigate the reliability of joint centre locations, one full movement trial was re-digitised twice, on separate occasions, and the three separate data outputs compared. RMSD and %RMSD analyses were then employed to determine

the joint centre location reliability and random error present (intra-digitiser reliability). Furthermore, digitiser accuracy and objectivity were established through the separate digitising of known locations and the comparison to another researcher who regularly used and was confident in using PEAK Motus (inter-digitiser reliability).

Sensitivity Analysis of Body Segment Inertia Parameters

Kerwin and Irwin (2006) varied the body segment inertia parameters of the gymnast by inputting one gymnast's inertia parameters to the inverse dynamics calculation of three gymnasts of varying height and mass. The influence on predicted bar forces were then reported. Building on from Kerwin and Irwin's (2006) sensitivity analysis, gymnast inertia parameters of three gymnasts approximately 50, 100 and 120% of the selected gymnast's mass were inputted and the influence on bar forces and knee, hip and shoulder joint moments, powers and work were determined through RMSD and %RMSD calculations.

5.2.4.3 Field versus Lab Analysis

In order to address the second aim of this study and evaluate the use of field based measurement in inverse dynamic analysis compared to their lab comparison, kinematic, kinetic and inertia variables were examined. To quantify any differences found RMSD (Equation 5.10) and %RMSD (Equation 5.11) were calculated utilising the direct lab measurement as the pseudo criterion and the indirect field measurement as the examined variable.

$$\text{RMSD} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_{lab} - x_{field}\right)^2}$$

[5.10]

RMSD = root mean square difference
n = number of samples
x_{lab} = lab data point
x_{field} = field data point

$$\%\text{RMSD} = \frac{\text{RMSD}}{\text{Max}_{lab} - \text{Min}_{lab}} \times 100$$

[5.11]

%RMSD = percentage root mean square difference

$RMSD$ = *root mean squared difference*

Max_{lab} = *Maximum lab data point*

Min_{lab} = *Minimum lab data point*

Kinematic Variables

Key differences between a lab based collection and an elite competition field set up could be regarded as the physical LED markers and marker boxes positioned on the gymnast's skin, obtainable sampling frequencies and the type of error present. Joint coordinate data collected by both the 3D video setup (field) and automated motion analysis system (lab) were inputted into the inverse dynamics analysis (Figure 5.8) and outputs compared.
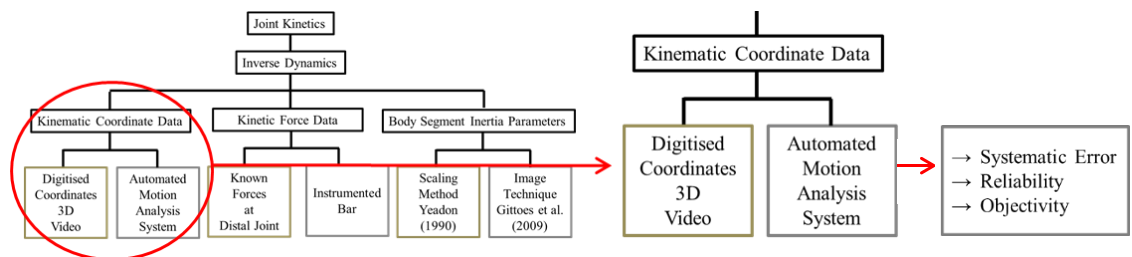
Figure 5.8. The comparative methods used to collect kinematic data in the **field** and **lab** to subsequently be inputted to IDA with systematic error, reliability and objectivity checks carried out on the lab based method.

3D video data were interpolated from 50 Hz to 200 Hz using a cubic spline function (Mathcad 14, Parametric Technology Corporation, USA) so that the field method could be validated against the lab method. RMSD analyses were applied to the joint kinetic data to determine if the method used in collecting joint coordinate data influenced bar forces and joint moment, power and work data.

The use of CODA for the collection of kinematic data introduces systematic error. Systematic error can be defined as a consistent incorrect measurement error (Challis, 2007). To establish this error, marker reliability was calculated by repeated marker placement during the static trial and differences between three trials calculated. The calculated systematic error would remain consistent throughout the analysed movement trials. Objective reliability in marker placement was also established by comparing the position of markers between the primary investigator and one other researcher who was confident in the process involved and regularly used the system. The above reliability

measures ensured that the direct lab based measurement was as close to the criterion measure as possible.

Kinetic Variables

As successfully used by Gervais (1993), predicted bar forces were calculated utilising known zero forces at the toes and an inverse dynamics analysis (as detailed in section 5.2.4.1). Employing comparable calibration techniques to Kerwin and Hiley (2003), recorded strain data were converted to directly measured bar forces using linear regression of the predetermined calibration data (section 5.2.2). Differences between the measured (lab) and predicted (field) bar forces (Figure 5.9) were quantified by calculating RMSD during the full longswing (circle angle of 135° to 450° for the longswing trials and 135° to release for the Tkachev trials). RMSD values were further divided by the range of the directly measured output in order to obtain relative differences across trials (%RMSD) (Equation 5.5).
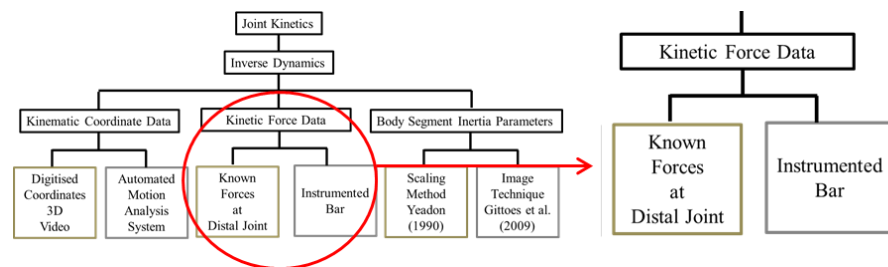
Figure 5.9. The comparative methods used to calculate bar forces in the **field** and **lab** to subsequently validate IDA in the prediction of bar forces.

Body Segment Inertia Parameters

Gittoes et al. (2009) developed an image-based method for obtaining anthropometric measurements to use as inputs into Yeadon's (1990) inertia model, which then determined individual specific body segment inertia parameters (Appendix III). The authors reported a 2.9% error when predicting whole-body mass compared to 2.1% reported by the direct measurement. This method was deemed a successful alternative combined with a less obtrusive collection and a less time consuming process for the elite athlete. RMSD analyses were employed in order to determine the influence of using the image-based approach and the scaled mass ratio correction factor in calculating bar force and joint moments, powers and work at the shoulders, hips and knees. Accuracy, reliability and objectivity of the lab (image based) approach were reported to justify the lab based method

as the criterion measure. Accuracy was determined by the calculated difference between predicted mass from the image technique and known mass. Reliability was determined by two repeated digitised images and the calculated difference between the originally calculated total body mass and the total body mass calculated from the re-digitised images. Finally, objectivity was determined through inter-digitiser comparisons and the difference between total body mass calculated from the principal investigators digitised image and the digitised image from an experienced digitiser.
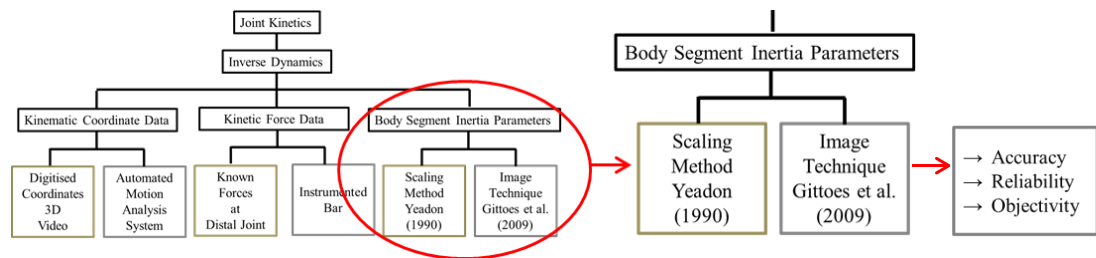
Figure 5.10. The comparative methods used to collect BSIP data in the **field** and **lab** to subsequently be inputted to IDA with accuracy, reliability and objectivity checks carried out on the lab based method.

5.2.4.4 Statistical Analysis

Tests for normality (Shapiro-Wilkes) and homogeneity of variance (Levene's test) with the alpha level set to $p \leq 0.05$ were carried out on discrete variables (peak bar forces, joint moments, joint powers and joint work) from the perturbed, field and lab based data. With the assumptions of an Analysis of Variance (ANOVA) met, an ANOVA was employed to quantify differences in the perturbed data and between the field and lab methods of approach.

5.3 Results

5.3.1 Reliability, Accuracy and Objectivity

Field Protocol: 3D Video

Joint coordinate reliability through repeated digitising in both the horizontal and vertical axis was between 0.006 m (wrist in the vertical) and 0.019 m (wrist in the horizontal) from a circle angle of 135° to release. Digitising accuracy of four known points and three known lengths (left and right high bar support and high bar length) was 0.016 m, 0.1% relative to the total field of view. Finally, inter-digitiser reliability for the same trials and from a circle

angle of 135° to release was 0.020 m. Influence of joint centre location on subsequent joint kinetics is reported further into this section.

Lab Protocol: Automated Motion Analysis

Marker placement reliability in the sagittal plane between three static trials was 0.003 m and between two different researchers was 0.003 m. A systematic error of 0.003 m can therefore be recognised in any differences between the field and lab based methods in determining joint centre location.

Lab Protocol: Image Based Body Segment Inertia Parameters

Reliability in the estimated total body mass of the gymnast was 0.25 kg equating to less than 0.4% difference between the gymnast's actual body mass. Accuracy in estimating the gymnast's total body mass was within 2.50 kg (4.0%) which was 1.1% higher than Gittoes et al. (2009). Inter-digitiser reliability estimated gymnast mass to within 0.20 kg (0.3%).

5.3.2 Errors associated with Inverse Dynamics Analysis

The following section focuses on the sensitivity analysis of the inputs to IDA collected utilising field based methods within the pseudo competition setup. Predicted bar forces, joint moments, joint powers and joint work were calculated using the original field based parameters for cut off frequency (6 Hz), joint centre location (virtual four segment model from the 3D video analysis) and body segment inertia parameters (93% of gymnasts total body mass). Separate analyses were then performed changing one of the parameters and then the influence on the inputs to inverse dynamics and joint kinetics reported. All analyses were carried out on the 3D video data.

Cut off Frequency

3D video data (field approach) were filtered using a 6 Hz cut off frequency based on a Winter's residual analysis (Winter, 2009). Predicted bar forces and joint kinetics were calculated and compared to the same outputs calculated using a 2.5, 5, 7.5 and 10 Hz cut off frequency.

Altering the cut off frequency either side of 6 Hz had little influence on the total body mass centre location in both the y and z axis. As expected the lower cut off frequency of 2.5 Hz showed the greatest differences in the y (RMSD = 0.038 m, %RMSD = 2.2%) and z direction (RMSD = 0.047 m, %RMSD = 2.9%). This is replicated in all joint centre locations in both axis with the maximum %RMSD being 3.2% for the ankle in the z axis filtered at 2.5 Hz. Cut off frequencies closest to the original 6 Hz (5 and 7.5 Hz) all

reported a %RMSD less than 0.6% for each of the joint centre locations throughout the longswing and longswing preceding the straddle Tkachev (Table 5.1).

Table 5.1. RMSD and %RMSD for total body mass centre, bar and joint centre locations collected using 3D video (field method) filtered at 2.5, 5, 7.5 and 10 Hz from a circle angle of 135° to release

	2.5 Hz		5 Hz		7.5 Hz		10 Hz	
	RMSD	%RMSD	RMSD	%RMSD	RMSD	%RMSD	RMSD	%RMSD
CMy (m)	0.038	2.2	0.006	0.4	0.006	0.4	0.013	0.8
CMz (m)	0.047	2.9	0.008	0.5	0.008	0.5	0.016	1.0
ybar (m)	0.006	4.1	0.001	0.7	0.001	0.7	0.002	1.3
zbar (m)	0.006	4.6	0.001	0.7	0.001	0.7	0.002	1.4
yshd (m)	0.026	2.4	0.005	0.5	0.004	0.4	0.009	0.8
zshd (m)	0.031	3.1	0.006	0.6	0.005	0.5	0.011	1.1
yhip (m)	0.045	2.2	0.007	0.4	0.008	0.4	0.015	0.7
zhip (m)	0.057	3.0	0.009	0.5	0.010	0.5	0.019	1.0
ykne (m)	0.063	2.4	0.010	0.4	0.010	0.4	0.020	0.8
zkne (m)	0.074	2.9	0.012	0.5	0.012	0.5	0.024	1.0
yank (m)	0.087	2.7	0.013	0.4	0.013	0.4	0.027	0.8
zank (m)	0.098	3.2	0.015	0.5	0.015	0.5	0.030	1.0

Figure 5.11a and b illustrate the influence of the cut off frequency on the predicted forces at the bar. The tuning of cut off frequency has a larger influence on predicted bar force in the horizontal axis than in the vertical (20-25% more), particularly at the peak forces. With the horizontal forces at the bar illustrating two points of peak force (approximately at a circle angle of 200° and 310°) compared to the one for vertical force (approximately 270°), a greater %RMSD was expected. Filtering at 2.5 Hz however had a greater effect on the vertical force particularly during the upswing (Figure 5.11b). Between the horizontal and vertical predicted forces there was less than 1% difference and all differences between selected cut off frequency and 6 Hz was less than 5.6% (Table 5.2). Employing a cut off frequency of 5 Hz provided lowest %RMSD of 1.2% and 1.0% in the y and z axis respectively.

As expected due to propagated error, joint moments at the shoulder were most effected by the changes in cut off frequencies ranging from 3.3%RMSD to 16.8%RMSD. Similarly to the predicted bar force data, the changes in cut off frequency (excluding the over filtering of 2.5 Hz) effected the peak moments primarily. With the shoulder joint moment profile illustrating more frequent oscillations than the lower joints, a greater chance of error was expected in the peak moments due to the location of differences (Figure 5.11c).
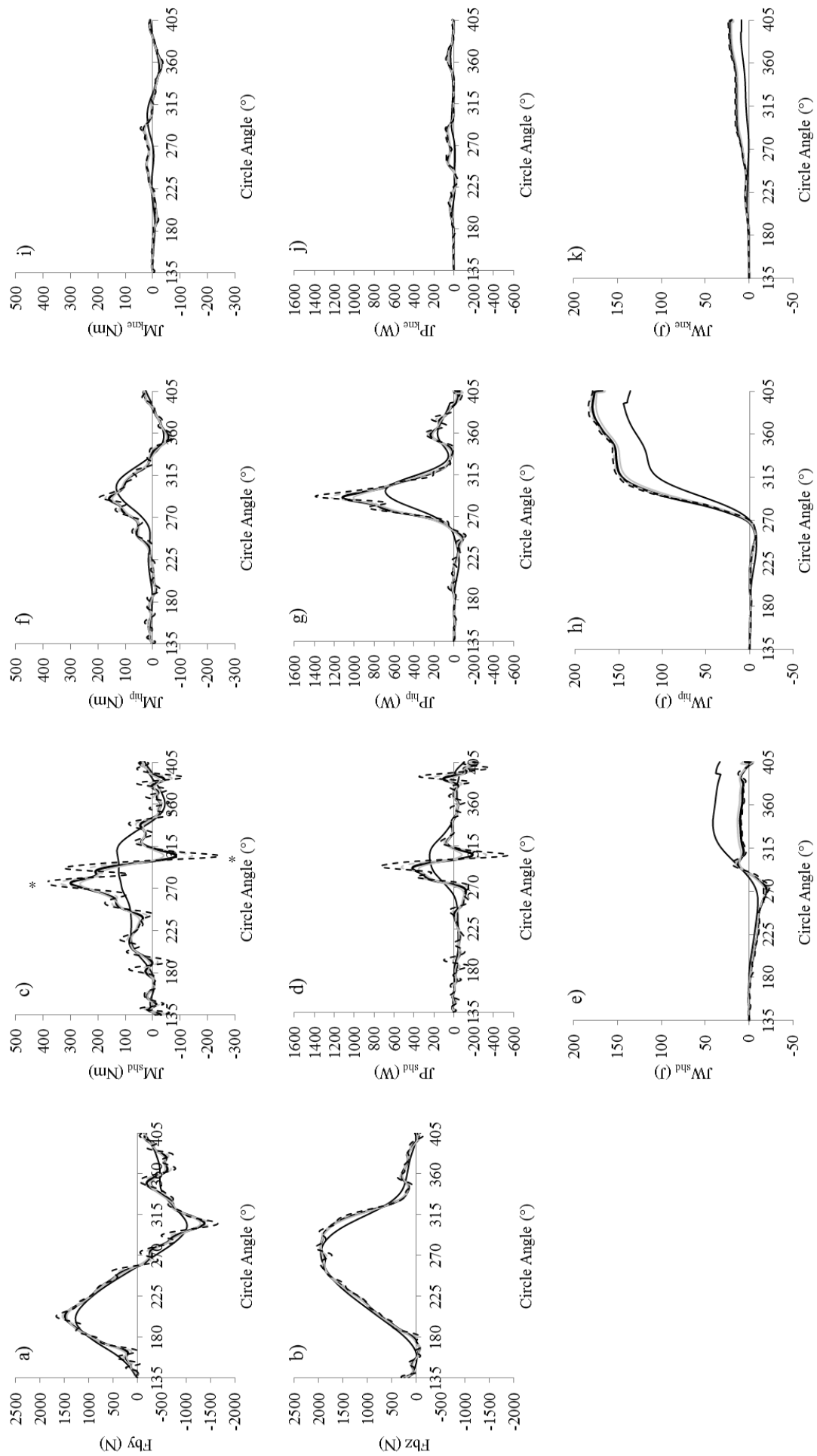
Figure 5.11. The influence of changing the cut off frequency from 6 Hz (-) to 2.5 Hz (-), 5 Hz (-), 7.5 Hz (--) and 10 Hz (--) on estimated bar forces (a-b) and joint kinetics at the shoulder (c-e), hip (f-h) and knee (i-j). * denotes a significant differences between 6Hz and 10Hz ($p \leq 0.05$).

Table 5.2. RMSD and %RMSD for selected kinetic variables locations calculated using 3D video data (field method) and filtered at 2.5, 5, 7.5 and 10 Hz from a circle angle of 135° to release

	2.5 Hz		5 Hz		7.5 Hz		10 Hz	
	RMSD	%RMSD	RMSD	%RMSD	RMSD	%RMSD	RMSD	%RMSD
F_{by} (N)	145.28	5.1	33.05	1.2	46.70	1.6	122.61	4.3
F_{bz} (N)	113.16	5.6	20.21	1.0	25.07	1.2	64.59	3.2
JM_{shd} (Nm)	64.45	16.8	12.54	3.3	17.70	4.6	47.47	12.3
JM_{hip} (Nm)	21.19	9.8	3.92	1.8	4.82	2.2	12.38	5.7
JM_{kne} (Nm)	10.05	15.2	1.56	2.4	1.49	2.3	3.34	5.1
JP_{shd} (W)	105.01	16.1	28.25	4.3	38.83	6.0	101.32	15.5
JP_{hip} (W)	115.55	9.6	23.13	1.9	26.10	2.2	62.84	5.2
JP_{kne} (W)	25.90	27.7	4.79	5.1	4.55	4.9	9.91	10.6
JW_{shd} (J)	18.10	56.1	2.09	6.5	1.32	4.1	2.25	7.0
JW_{hip} (J)	25.34	13.5	2.89	1.5	1.83	1.0	2.83	1.5
JW_{kne} (J)	7.90	35.9	1.08	4.9	0.68	3.1	1.10	5.0

Joint moments at the hip joint reported the lowest %RMSD for all cut off frequencies (excluding 10 Hz) with the largest being 9.8% at 2.5 Hz. Filtering at 2.5 Hz predominantly omitted peak joint moments, however, this was not reported at the hip joint. Figure 5.11c-e illustrates the over smoothed effect of the over filtered data attributing to the largest %RMSD values. In contrast, filtering at 10 Hz largely accentuated peak moments at all joints causing the relatively large %RMSD, however only a significant difference was found at the shoulder joint ($p \leq 0.05$) at a circle angle of 270°. Joint moment data filtered at 7.5 Hz also marginally over calculated peak joint moments (Figure 5.11c-e) but %RMSD values were only 40-45% of those calculated for a 10 Hz cut off filter (Table 5.1). Calculated joint moments filtered at 5 Hz for the shoulder, hip and knee were less than 3.5% different when comparing to the original cut off frequency of 6 Hz. The lowest %RMSD of 1.8% was calculated for the hip joint moment when filtered at this cut off frequency.

A repeated finding illustrated in the joint power data was the over smoothing of data when the lower cut off frequency was applied (2.5 Hz) and an over estimation of peak data when the higher band width was applied (7.5 Hz and 10 Hz). The shoulder joint was influenced most by the over accentuated peak power values (Figure 5.11d) and the knee joint most effected by the over smoothing of the data (Figure 5.11j). The hip joint reported similar, if not lower, differences than the joint moment data between filtering at 6 Hz and the other selected cut off frequencies (Table 5.2).

Applying a cut off frequency over 50% less than the calculated cut off frequency (2.5 Hz) affected joint work at the shoulder by over 55%. Figure 5.11e illustrates the overestimated

of joint work at the shoulder throughout the ascending phase of the skill. Joint work at the hip and knee joints utilising a cut off frequency of 2.5 Hz was also the greatest discrepancy from 6 Hz, however for these selected joints, joint work was under estimated.

Differences between joint work employing the selected cut off frequency of 6 Hz and the upper band widths (7.5 and 10 Hz) were less than those reported for joint power. During the ascent phase (post 270°) joint work increased and was maintained up to release. With no clear peaks in the data, common over estimation of peak data by the 7.5 and 10 Hz cut off frequency did not occur (Figure 5.11h and k).

Joint Centre Location

When comparing the gymnast's joint centre locations from the original digitised data and the repeated trials, the greatest differences were observed at the wrist and were greater than all other joint centres. With the wrist joint excluded, remaining differences were less than 1.3%RMSD throughout the entire skill (135° to release). The calculated centre of mass location for the same time period varied greater between repeated trials however it remained less than 0.025 m equating to 1.5%RMSD (Table 5.3).

Table 5.3. RMSD and %RMSD for horizontal and vertical centre of mass and joint centre locations from 3D video data (field) between the original and repeated digitised trials from a circle angle of 135° to release

	Original Vs. Repeat 1		Original Vs. Repeat 2	
	RMSD	%RMSD	RMSD	%RMSD
Cy (m)	0.023	1.4	0.023	1.4
Cz (m)	0.022	1.4	0.022	1.4
ywri (m)	0.023	8.3	0.012	4.8
zwri (m)	0.008	2.5	0.007	2.5
yshd (m)	0.009	0.8	0.012	1.1
zshd (m)	0.007	0.6	0.014	1.3
yhip (m)	0.012	0.6	0.019	0.9
zhip (m)	0.010	0.5	0.016	0.8
ykne (m)	0.016	0.7	0.014	0.6
zkne (m)	0.007	0.3	0.009	0.4
yank (m)	0.008	0.3	0.009	0.3
zank (m)	0.008	0.3	0.010	0.3

The influence of the above coordinate differences were highlighted in the predicted bar force data with a difference between 5-6%RMSD both horizontally and vertically (Table 5.4). For the predicted horizontal force in particular, greater differences between the

digitised data sets occurred during the last 60° of the skill that coincided with the final pull on the high bar (Figure 5.12a).

Differences between re-digitised data sets increased by over 100% when joint moments at the shoulder were calculated, which could be expected using an inverse dynamics analysis. Illustrated in Figure 5.12c are the key phases of the preparatory longswing where these differences were greatest, predominantly either side of the peak joint moment prior to a circle angle of 235° and post 290°. Estimated joint moments at the hips and knees were approximately 40% less different than at the shoulder during the toe up method when comparing to the original data set; approximately 7.3%RMSD (Table 5.4). The greatest difference for the lower joints occurred as an under estimated peak moment when the gymnast passed underneath the bar at a circle angle of approximately 275° (Figure 5.12f and i).

Excluding the knee joint, joint power differences between the original and re-digitised data were lower than those reported for joint moments (less than 8.5%RMSD). Hip joint powers had the greatest difference around a circle angle of 275° which coincided with the location of peak joint power, whereas the greatest difference at the shoulder joint was at a circle angle of 290° during a second negative peak power. Similarly at the hip joint the second peak power (approximately 360°) was calculated earlier and lower than the original peak power output (Figure 5.12g and j) contributing to the 5-6%RMSD.

Table 5.4. RMSD and %RMSD for estimated horizontal and vertical bar forces and joint kinetics between the original and repeated digitised trials from a circle angle of 135° to release

	Original Vs. Repeat 1		Original Vs. Repeat 2	
	RMSD	%RMSD	RMSD	%RMSD
Fby (N)	155.49	4.9	187.82	6.0
Fbz (N)	129.75	5.6	115.85	5.0
JM_{shd} (Nm)	65.95	11.6	57.75	10.2
JM_{hip} (Nm)	19.96	6.6	22.26	7.3
JM_{kne} (Nm)	6.14	6.7	5.84	6.4
JP_{shd} (W)	140.62	8.4	124.39	6.9
JP_{hip} (W)	97.92	5.4	119.96	6.6
JP_{kne} (W)	21.77	10.4	15.36	7.3
JW_{shd} (J)	4.41	5.5	9.64	12.1
JW_{hip} (J)	11.97	5.0	5.89	2.5
JW_{kne} (J)	1.12	3.1	0.70	1.9
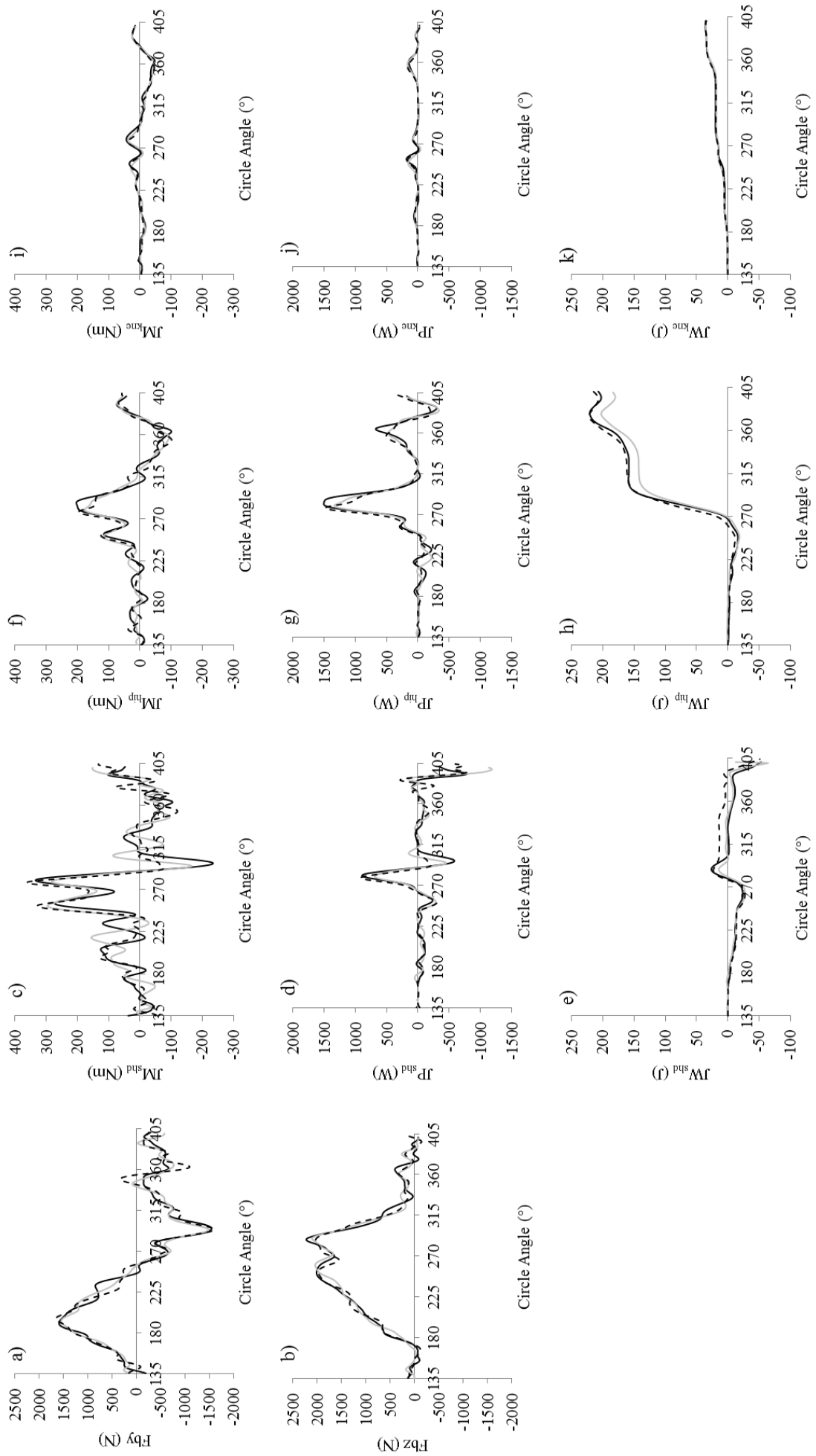
Figure 5.12. The influence of re-digitising on estimated bar forces (a-b) and joint kinetics at the shoulder (c-e), hip (f-h) and knee (i-j). Original (-), Repeat 1 (–) and Repeat 2 (--)

Differences between the two re-digitised data sets and the original data were greatest when calculating joint work. %RMSD values were not consistent between the two re-digitised trials with joint work at the shoulder and hip differences increasing by at least 100% (Table 5.4). The random error through manual digitising and its influence on joint work calculation is illustrated in Figure5.12e with the over estimation of joint work after a circle angle of 290°. At this same phase in the preceding longswing, joint work calculated at the hip was underestimated relative to the original data set by one of the re-digitised trials. However, the %RMSD throughout the whole skill was less than 5.0%RMSD for both re-digitised trials. Joint work calculated for the knee joint had the lowest differences between the originally digitised trial and the re-digitised data sets; less than 3.1%RMSD.

Body Segment Inertia Parameters

When body segment inertia parameters (BSIP) were altered by 50% and 118% of the gymnast's total body mass, small differences less than 3.1%RMSD were reported for predicted bar force and joint moment data (Table 5.5). Data were perturbed around the original BSIP data that equated to 93% of the gymnast's total body mass. For BSIP data 25% above the original data used, bar forces differed by 0.6%RMSD in the horizontal and 0.7%RMSD in the vertical. Gymnast BSIP data 50% less than the original gymnast profile reported differences of less than 1.9%RMSD in both the horizontal and the vertical. The greatest differences occurred around the peak predicted bar forces (Figure 5.113a and b).

Table 5.5. RMSD and %RMSD for selected variables utilising body segment inertia parameters for a gymnast 50% and 118% of the selected gymnast's total body mass from a circle angle of 135° to release

	BSIP 50%		BSIP 118%	
	RMSD	%RMSD	RMSD	%RMSD
F_{by} (N)	40.94	1.4	18.10	0.6
F_{bz} (N)	39.84	1.9	15.00	0.7
JM_{shd} (Nm)	10.68	2.8	9.71	2.5
JM_{hip} (Nm)	5.38	2.4	4.74	2.1
JM_{kne} (Nm)	1.69	2.5	2.09	3.1
JP_{shd} (W)	16.39	2.5	14.04	2.1
JP_{hip} (W)	31.68	2.5	25.54	2.0
JP_{kne} (W)	3.64	3.5	4.26	4.1
JW_{shd} (J)	1.14	3.7	3.52	11.4
JW_{hip} (J)	8.34	4.4	7.46	4.0
JW_{kne} (J)	1.08	4.8	0.29	1.3
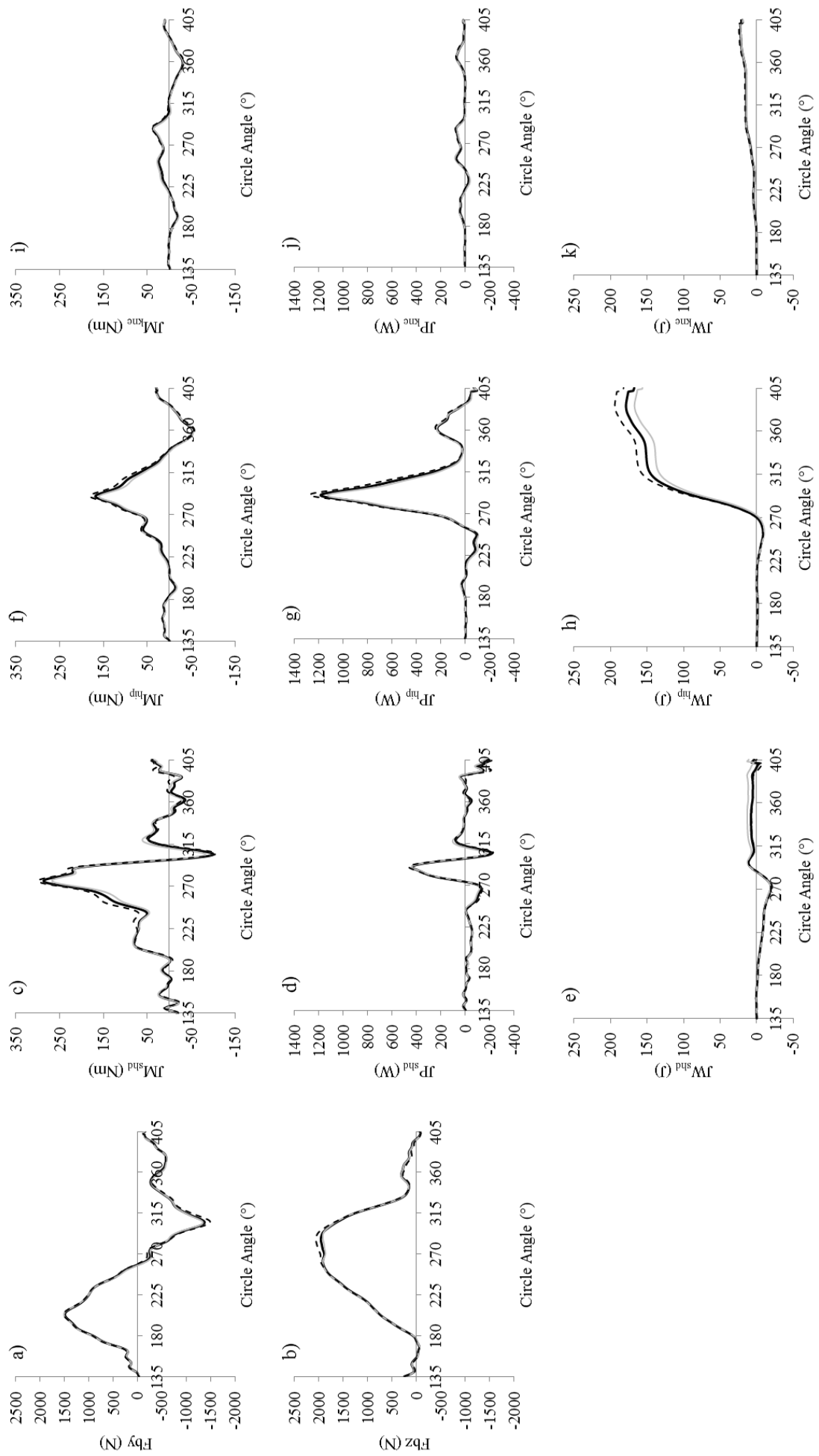
Figure 5.13. The influence of change of BSIP to 50% (– –) and 118% (–) of the gymnasts total body mass (93%) (–) on estimated bar forces (a-b) and joint kinetics at the shoulder (c-e), hip (f-h) and knee (i-j).

Joint moment differences between the original and perturbed data sets were smallest at the hip joint (Table 5.5). The differences between the data sets occurred during the ascent phase of the preparatory longswing between a circle angle of 290° and 320° (Figure 5.13f). The differences in shoulder joint moments between the three trials occurred prior to the gymnast passing underneath the high bar during the descent phase from 220° to 260°. Differences in knee joint moments occurred consistently throughout the whole skill.

Joint powers calculated utilising the perturbed data sets reported similar differences between the original data for both the shoulder and hip joints. The differences were greatest at the point of peak power and were between 2.0 and 2.5%RMSD. The knee joint illustrated the greatest %RMSD between 3.5 and 4.1%RMSD for the lower and upper BSIP alterations respectively. Similarly to the joint moment data, this was due to consistent differences throughout the whole skill (135° to release) as opposed to at the single peak power (Figure 5.13j).

Differences in joint work calculations decreased working from the toe up for the gymnast profile 50% less than the original, but increased for the 118% profile. Excluding the shoulder joint work when BSIP parameters were adjusted to 118%, differences remained less than 4.8%RMSD. Increasing the gymnasts total body mass to 118% resulted in an increase in shoulder joint work calculated after a circle angle of 300°. For the hip joint however the increased profile resulted in a decrease in the joint work calculated during the same phase of the skill (4.0%RMSD). Similar %RMSD values for the hip and knee joint when utilising the 50% BSIP profile were as a result of an over estimation of joint work in the final ascent phase of the preparatory longswing (Figure 5.13h and k).

5.3.3 Evaluation of Field versus Lab Based Methods

The following section focuses on the evaluation of using field based measurements as the inputs to IDA, compared to their comparative lab based measures. The same movement trials of three sets of five longswings and five straddle Tkachevs were analysed and the direct lab based methods were assumed as the criterion measure.

Predicted bar forces, joint moments, powers and work were calculated from original data inputs derived from the 3D video analysis in the pseudo competition setup (field) and compared to outputs using their CODA (lab) counterparts. Digitised kinematic data from the 3D video setup, kinetic data from the assumption of zero forces and joint moments at the gymnast's toes and finally body segment inertia parameters scaled from a gymnast database to the gymnast formulated the original field data inputs. One of the above

variables was then altered to the lab based alternative (automated motion analysis system, directly measured forces from instrumented bar or body segment inertia parameters from the image approach) and the joint kinetics calculated and compared to the original data.

Kinematic Data

Differences between bar and joint centre locations collected by 3D video (field) and automated motion capture (lab) were less than 0.046 m (Table 5.6) from a circle angle of 135° to release. All joint centres were less than 4.0%RMSD with the shoulder joint emitting the largest difference in the horizontal direction at 3.8%RMSD. The bar centre locations revealed greater differences of 14.3%RMSD and 10.0%RMSD in the horizontal and vertical direction respectively but the range of movement was a lot lower with the relative difference only being 0.023 m and 0.014 m.

Systematic error from the static trial was calculated as an average of 0.003 m for joint centre location defined by the CODA markers that can be taken into consideration when examining Table 5.6. The %RMSD values for joint centre location between the lab and field based methods were also consistent across all trials with a maximum standard deviation value of 0.7%.

Table 5.6. RMSD and %RMSD for selected kinematic and kinetic variables calculated using kinematic data derived from lab (CODA) and field (3D video) based methods from a circle angle of 135° to release

	Kinematics			Kinetics	
	RMSD	%RMSD		RMSD	%RMSD
CMy (m)	0.021	1.3	Fby (N)	235.34	9.8
CMz (m)	0.019	1.1	Fbz (N)	144.78	6.5
ybar (m)	0.023	14.3	JM_{shd} (Nm)	106.75	23.8
zbar (m)	0.014	10.0	JM_{hip} (Nm)	44.31	22.6
yshd (m)	0.045	3.8	JM_{kne} (Nm)	14.12	20.8
zshd (m)	0.029	2.6	JP_{shd} (W)	208.47	24.0
yhip (m)	0.044	2.2	JP_{hip} (W)	265.51	29.4
zhip (m)	0.042	2.1	JP_{kne} (W)	30.89	20.5
ykne (m)	0.046	1.8	JW_{shd} (J)	18.49	33.7
zkne (m)	0.036	1.4	JW_{hip} (J)	50.96	40.4
yank (m)	0.030	0.9	JW_{kne} (J)	5.40	23.6
zank (m)	0.041	1.3			

Vertical and horizontal predicted bar forces were less than 10.0%RMSD between the CODA and 3D video methods of collecting kinematic data; both methods utilising the

assumption of zero forces at the toes. Figure 5.14a and b illustrate that at the time of peak horizontal and vertical bar force the digitised coordinate data appeared to overestimate the predicted bar forces. The time of peak force was also estimated later utilising the digitised data when compared to the CODA data contributing to the larger %RMSD values. The first peak horizontal force was estimated 14% significantly greater in the 3D video method and 11° later with the second being 42% significantly greater and 15° later. For predicted vertical force at the bar the peak values were similar (within 3%) but using the digitised coordinate data the time of peak force occurred 28° later in the circle. Similarly to the joint centre locations between the CODA and 3D video methods, the %RMSD values were relatively consistent with horizontal force differences being within 2.6%RMSD across all trials and vertical force 1.2%RMSD.

Differences in joint moments calculated from using kinematic data collected from CODA and 3D video digitisation increased substantially compared to the coordinate and bar force data. The differences increased from the knee joints to the shoulder joints (Table 5.6) and ranged from 20.8%RMSD to 23.8%RMSD. Although the differences reported are relatively high, Figure 5.14c, f and i illustrate that the general wave form for the joint moments are similar with the greatest differences occurring in the frequency of the data. The CODA constructed data has a greater number of oscillations than the 3D video data that appears smoother, which may be a result of the increased sampling frequency during collection.

For each of the three joint moments, differences between the CODA and 3D video data appears to be smaller in the ascending phase of the preparatory longswing (from a circle angle of 315° to 405°). The greatest differences occur around a circle angle of 270° when the gymnast passes beneath the high bar. At this point the joint moments calculated from the 3D video data reached its peak joint moment whereas the CODA data appeared to decrease to a trough. Excluding the joint moments at the shoulder, this makes peak moments reported by the 3D video to be considerably greater than the CODA data (Figure 5.14f and i). Peak joint moments utilising the kinematic data from CODA are 57% and 52% of the 3D video counterpart for the hip and knee joint respectively.

The consistency in the %RMSD values for joint moment data was relatively high when observing the shoulder and hip joint moments, excluding one anomaly trial. With the consistently different trial removed, the %RMSD was within 0.8%RMSD across all trials for the longswing and preparatory longswing. A large difference between methods that holds consistency across trials provides confidence in the systematic differences between

Figure 5.14. Estimated bar force (a-b) and joint kinetics at the shoulder (c-e), hip (f-h) and knee (j-k) calculated using the automated motion analysis system (black) and the 3D video digitising (grey). * denotes a significant difference ($p \leq 0.05$).

the two approaches. The knee joint however was less consistent across all trials increasing to a 2.5%RMSD standard deviation.

Differences between joint powers calculated using field (3D video) and lab (CODA) kinematics were similar to the joint moment differences for the shoulder and knee joints (Table 5.6). The hip joint however increased to 29.4%RMSD which can be partially accounted for by the significantly large difference in peak hip power. Figure 5.14g illustrates that using digitised coordinate data over calculated peak hip power by 55% compared to the CODA coordinate data at a circle angle of approximately 290°.

Consistency in %RMSD values across all trials decreased when looking at joint power calculations utilising different methods of collection. %RMSD standard deviation values were between 9.5 and 5.0%RMSD with the shoulder producing the largest and the knee the smallest. The decrease in consistency suggests a move from systematic differences to differences caused by random error as opposed to systematic error.

Large differences between joint work calculated with the lab and field kinematic data occur, particularly at the hip joint (Table 5.6). A 40.4%RMSD between the lab and field at the hip joint was greatest when joint work was generated on the ascent phase of the preparatory longswing (Figure5.11h). Peak joint work at the hip was significantly greater when using kinematic data from the field. With the consistency decreasing further to an 18%RMSD standard deviation at the hip, caution should be taken when comparing different methods of approach in the calculation of joint work.

Kinetic Data

In order to validate the assumption of zero forces at the toes as an input to IDA, predicted bar forces utilising this field method were compared to directly measured bar forces (lab). Differences between the two methods were 11.6%RMSD in the horizontal and 10.5%RMSD in the vertical from a circle angle of135° to release. IDA from the toes up to the bar significantly over predicted peak forces for both the horizontal and vertical bar forces (Figure 5.15). Horizontal force predicted from IDA reported a peak in force at a circle angle of 300° that suggested a pull on the bar by the gymnast during the ascent phase of the longswing. However, this action was not as emphasised in the directly measured horizontal force.

For all trials the standard deviation of %RMSD between measured and predicted bar forces was 1.7%RMSD for horizontal bar force and 1.5%RMSD for vertical; highlighting a consistent difference between the two methods.
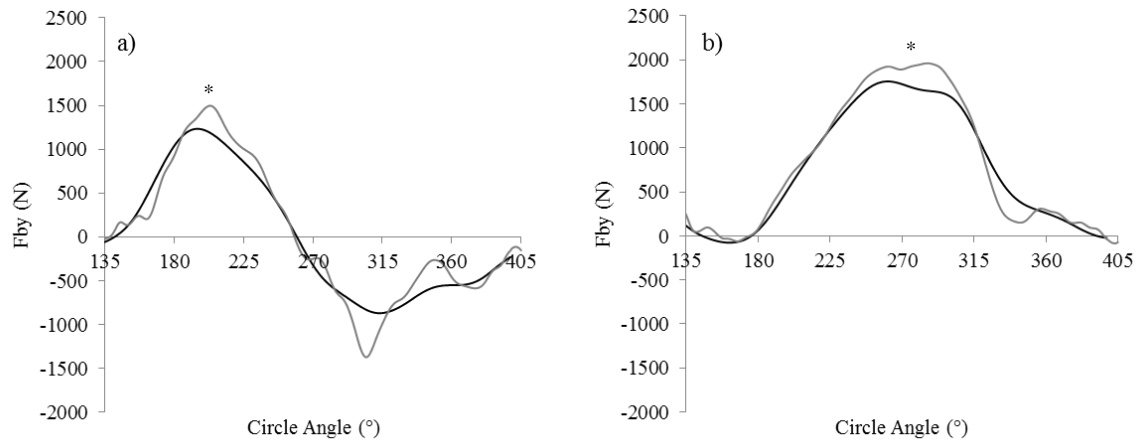
Figure 5.15. Directly measured (black) and predicted (grey) horizontal (a) and vertical (b) bar force. * denotes a significant difference ($p \leq 0.05$).

Body Segment Inertia Parameters

Yeadon's (1990) scaling method of using gymnast height and mass and a mass ratio correction factor determined the BSIP method within the field environment. Predicted bar forces and joint kinetic outputs using this field method were compared to those calculated using BSIP from Gittoes et al's. (2009) image approach (lab method). The image approach incorporated the input of segment lengths, widths and depths derived from digitised images of the gymnast into Yeadon's (1990) geometric model.

A change in the methods used in collecting body segment inertia parameters from the lab to the field changed the kinematic data marginally (Table 5.7). The largest difference was found at the vertical ankle joint location at 0.012 m. Joint centre RMSD values were calculated to be around 0.5%RMSD or lower of the range of the coordinate data during the preparatory longswing.

Horizontal and vertical predicted bar forces calculated utilising the scaling method of Yeadon (1990) were within 2.0%RMSD of the same predicted force values when the image approach of Gittoes et al. (2009) was used. Figure 5.16 illustrates how the greater differences were at the onset of peak force with the scaling method predicting lower peak forces than the image based approach. For all trials the %RMSD values were within 0.3%RMSD for both horizontal and vertical force highlighting consistency in the differences reported.

Table 5.7. RMSD and %RMSD for selected kinematic and kinetic variables calculated using BSIP data derived from scaling (field) and image (lab) based methods from a circle angle of 135° to release

	Kinematics			Kinetics	
	RMSD	%RMSD		RMSD	%RMSD
CMy (m)	0.011	0.7	Fby (N)	51.69	1.8
CMz (m)	0.008	0.5	Fbz (N)	42.08	2.0
ybar (m)	0.001	0.4	JM$_{shd}$ (Nm)	38.20	7.2
zbar (m)	0.001	0.6	JM$_{hip}$ (Nm)	10.31	4.0
yshd (m)	0.003	0.3	JM$_{kne}$ (Nm)	4.01	5.6
zshd (m)	0.003	0.3	JP$_{shd}$ (W)	60.85	7.1
yhip (m)	0.006	0.3	JP$_{hip}$ (W)	66.54	4.4
zhip (m)	0.007	0.4	JP$_{kne}$ (W)	7.52	7.5
ykne (m)	0.007	0.3	JW$_{shd}$ (J)	14.89	31.1
zkne (m)	0.010	0.4	JW$_{hip}$ (J)	19.53	8.9
yank (m)	0.008	0.3	JW$_{kne}$ (J)	0.52	2.2
zank (m)	0.012	0.4			

When calculating joint moments using the field and lab inertia sets the greatest differences were found around the base of the longswing (270°) which incorporated the peak joint moments. For all three joint moments the scaling method of Yeadon (1990) calculated the peak moments lower than that of the image method of Gittoes et al. (2009). The shoulder and knee joints were influenced more than the hip (7.2%RMSD and 5.6%RMSD respectively) with the scaling method over calculating on the ascent of the longswing for the shoulder joint moments and during the descent for the knee joint moments (Figure 5.16c, f and i). The %RMSD values for the hip and knee were consistent across all trials with the differences remaining within 0.9%RMSD. The shoulder however was more variable with a standard deviation of 1.9%RMSD.

Joint powers calculated at the shoulder and hip differed marginally from that of the joint moment calculations. The scaled inertia set, similarly to joint moments, calculated the peak powers lower than the image based inertia set (45% lower at the shoulder and 15% lower at the hip). The knee joint increased to 7.5%RMSD due to the increased number of peaks throughout the joint power profile and therefore an increased occurrence of peak power differences, both above and below that of the image based method moments (Figure 5.16d, g and j). Variation in the joint power differences across all trials was less than 1.6%RMSD with the hip joint only reporting 0.2%RMSD, highlighting systematic differences as opposed to random error.
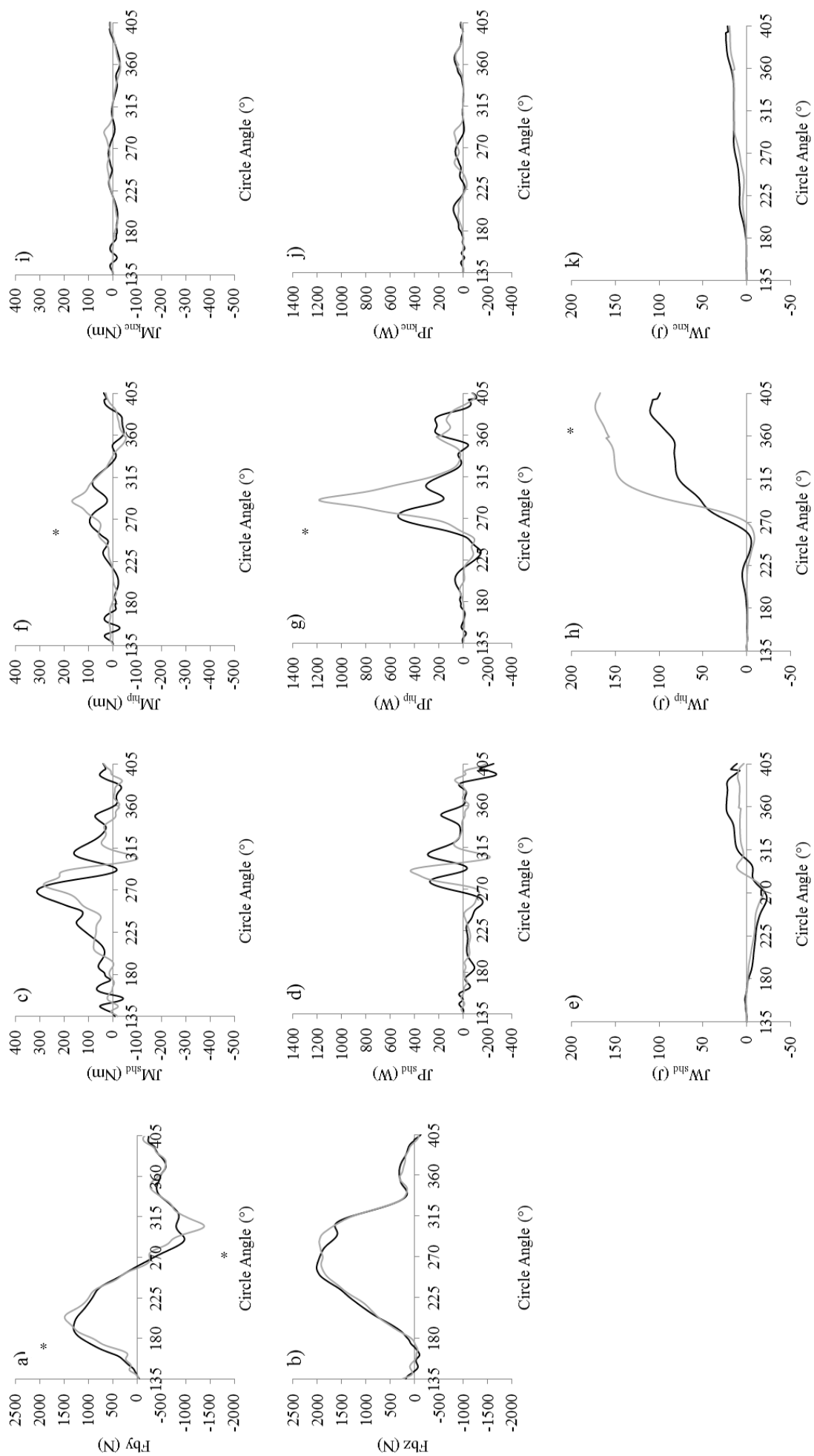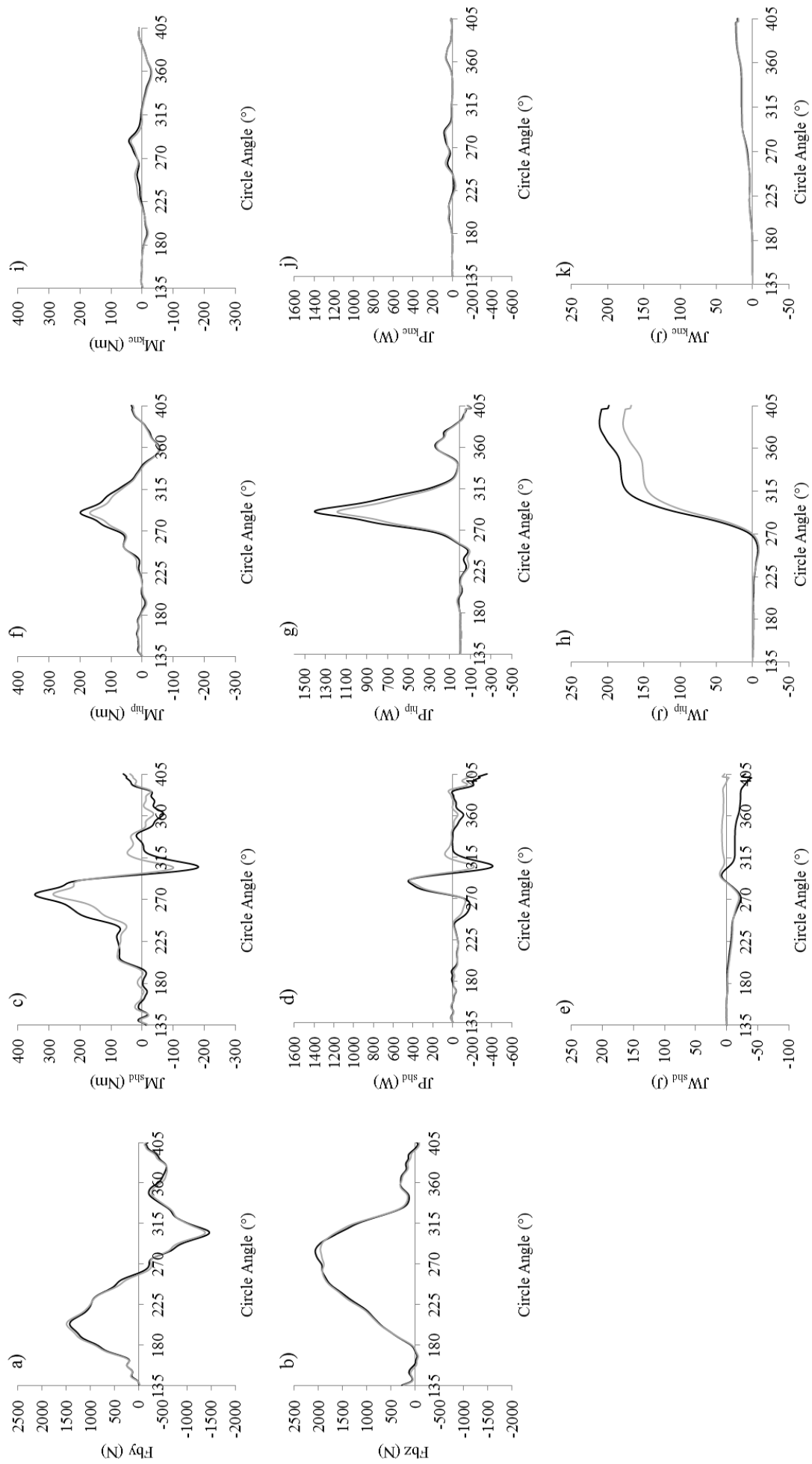
Figure 5.16. Estimated bar force (a-b) and joint kinetics at the shoulder (c-e), hip (f-h) and knee (j-k) calculated using body segment inertia parameters derived from Gittoes et al's (2009) image approach (black) and Yeadon's (1990) scaling method (grey).

The field based BSIP data calculated through Yeadon's (1990) scaling method calculated the joint work at the shoulder considerably higher than that of Gittoes et al. (2009). The 31.1%RMSD reported in Table 5.7 was greatest from a circle angle of 290° to release. Joint work calculated at the hip joint through the scaled approach was lower than that of the image approach for both the hip and knee joint, however the hip joint work difference was greater than that of the knee (8.9%RMSD compared to 2.2%RMSD). Consistency in the shoulder joint work %RMSD was low with their being a 12%RMSD variability across all trials compared to 1.5%RMSD at the hip and 4%RMSD at the knee.

5.4 Discussion

Data collected at a major international competition such as the Olympic Games is regarded as elite data at the highest possible level with maximum ecological validity. Gymnasts are performing at their maximum, against equal opposition and could obtain International recognition from good results. However, direct methods of collecting kinetic data are unfortunately not possible in this environment and indirect methods such as those utilised by Gervais (1993), Hiley et al. (1999), Kerwin and Hiley (2003) and Kerwin and Irwin (2006) have to be employed. Inverse dynamic analyses (IDA) is often the preferred approach (Winter, 2009), however there is uncertainty in the way that joint moments are calculated (Challis and Kerwin, 1996). Therefore the aim of the chapter was to investigate the errors associated with an inverse dynamics analysis in the field, specifically focusing on the sensitivity of body segment inertia parameters, estimation of joint centres and the measurement of positional data which Challis and Kerwin (1996) reported had a high influence on associated errors. Once the sensitivity of these parameters was established, the comparison of these measures with their lab based, gold standard alternatives (Elliott and Alderson, 2007) were then examined. A pseudo competition arena set up in a controlled lab environment enabled both methods of data collection to be utilised simultaneously. The underlying purpose of Chapter 5 was to establish a known error of an inverse dynamics analysis conducted in the field in order to have confidence in the mechanical findings and explanatory kinetics of the preparatory longswing. Justifying indirect methods in collecting elite data from top level competitions provides an assessment of quality data collection processes and provides insight into the musculoskeletal dynamics that generate movement (Bartlett, 1997) through elite kinetic and energetic data.

5.4.1 Sensitivity Analysis

One of the key findings from Challis and Kerwin (1996) was that error associated with IDA was most prominent in the determination of kinematic positional data. Vieten (1999) highlighted the importance of filtering positional data and concurred that IDA depends heavily on the quality of the kinematic data inputted. Kinematic data collected in the field and processed at a variation of cut off frequencies (2.5, 5, 7.5 and 10 Hz) were perturbed around the original processed data which was filtered at 6 Hz. Less than 0.7%RMSD was found between the joint coordinate data when filtered at the two closest cut off frequencies to the original. Although these differences were small, differentiation of the position and orientation data adds more uncertainty to the subsequent velocity and acceleration data that are not measured directly and influence the proceeding joint kinetic data (Challis and Kerwin, 1996). Looking further into the influence of cut off frequency on the kinetic data, greater effects were found on the predicted horizontal bar force compared to the vertical bar force utilising the toe up method; with differences predominately at maximum and minimum bar force. This may be due to the fact the bar forces in the horizontal direction went through two clear peaks at an approximate circle angle of 200° and 310° compared to the one in the vertical direction at approximately 270° (Figure 5.8a and b). The differences between the horizontal and vertical %RMSD range between 25% for the higher cut off frequencies and 15% for the lower two, implying that the difference could be attributed to twice the number of peaks. Kerwin and Irwin (2006) altered cut off frequencies between 3.6 Hz and 7.6 Hz and concurred with the current study to report minimal influence on the differences found between predicted and measured bar forces.

Deviating 1-2 Hz from the original 6 Hz was found to create up to a 4.6% difference on the joint moments at the knee, hip and shoulder joints. This highlights the importance of a comprehensive residual analysis heading into the following kinetics chapter. Joint moments at the hip illustrated the lowest %RMSD between cut off frequencies with moments at the shoulder being the highest. The latter of this result was expected due to the propagation of error defined by Challis (1996) as the error from one calculation transferring into another which is present within inverse dynamic analyses.

Joint power differences at the hip joint between the original and perturbed cut off frequencies remained similar if not lower than the joint moment data. Similarities in the hip joint profiles for these two variables may provide reasoning for the similar %RMSD values with one clear peak in joint moment and power as the gymnast began the ascent phase at around 290°. Increases in %RMSD values at the shoulder and knee joints when

calculating joint powers may be due to the increased uncertainty when differentiating in order to calculate angular velocities. There were no differences in the reliability for location of the three joints however the angular velocity reliability was slightly lower at the shoulder and knee joints (5.1 and 8.9%RMSD compared to 3.6%RMSD at the hip).

Irwin and Kerwin (2006) reported that the majority of work done in the general longswing was during the ascent phase of the swing of which this study on the preparatory longswing concurs. For each joint there is a rapid increase in joint work from around 270° that then remains consistent or with a gradual increase after 300°. Without a clear peak in joint work, the higher cut off frequencies (7.5 and 10 Hz) do not over accentuate the joint work data and the %RMSD remain low (less than 7.0, 1.5 and 5.0%RMSD at the shoulder, hip and knee respectively). When applying a filter of 2.5 Hz the joint work data is influenced differently between the three joints. Joint work at the shoulders was over estimated by 56.1%RMSD with the hip and knee joints being underestimated by 13.5 and 35.9%RMSD respectively. The difference illustrated at the shoulder joint was due to the over smoothed data excluding the negative peak in the shoulder joint power curve, therefore over calculating the area underneath the joint power curve and consequently the work done in comparison to the higher cut off frequencies.

Challis and Kerwin (1996) emphasised the importance of joint centre location by stating that the resultant joint moment is calculated with reference to the defined joint centre location. During the digitising process for collating joint coordinate data from the 3D video set up, genuine variability was attained with the user making a judgement of where the joint centre locations were for both the left and right side. Digitising reliability was calculated between 0.006 m and 0.019 m and the influence on bar force and joint kinetics further investigated.

Bar force data varied between 5.0 and 6.0%RMSD in both the horizontal and vertical with the greatest difference during the final 60° of the preparatory longswing. The differences leading up to release may be due to the bar obstructing the wrist markers and the side of the gymnast furthest away from the camera being more difficult to view during this phase in the longswing, influencing the digitised joint coordinate input to IDA. Although coordinate data was reliably digitised within 1.3%RMSD (excluding the wrist joint), a combination of all coordinate variability from the toe up to the bar would have been included in the IDA calculation.

At the shoulder joint, the final 60° of the circle angle was also a key phase in the preparatory longswing where joint moments and powers were particularly sensitive to the

re-digitised coordinate data, possibly highlighting this difficulty in estimating joint centre location. Due to unforeseen circumstances such as equipment position and nature of the gymnast's movement patterns, the level of estimation of joint centres is sometimes increased.

Through the sensitivity analysis of joint centre estimation in the current study, a confidence within 12.1%RMSD was reported for subsequent joint kinetic analyses. The 12.1%RMSD confidence level compared favourably with Irwin (2005) who reported differences in joint kinetics when comparing repeated digitisations to be within 11%RMSD.

Kerwin and Irwin (2006) investigated the influence of varying the body segment inertia profiles on predicting bar forces through IDA. IDA for a gymnast with mass 55.56 kg and BSIP profile of 70.39 kg (approximately 25% greater) were calculated. Differences between predicted and measured bar forces increased by 3.0% in the horizontal and 5.5% in the vertical axis. The current study acknowledged a 1.4%RMSD in the horizontal and a 1.9%RMSD in the vertical bar forces for a gymnast with a 50% decrease in their BSIP profile. Challis and Kerwin (1996) and Robertson et al. (2014) reported that the influence of changes in body segment inertia parameters on the calculation of joint moments had limited effect on IDA inaccuracies. This study concurred with their result with changes in the body segment inertia parameters only producing a 3.1%RMSD or less difference for joint moments at the shoulder, hip and knee joints. Therefore, in field situations where anthropometric data is not available and gymnasts are matched to their closest inertia profile from an inertia dataset (Yeadon, 1990), differences in predicted bar forces and joint moments are minimal even up to 50% of the gymnast's total body mass.

Joint power and joint work calculations were marginally affected more so by changes in body segment inertia parameters, however differences less than 5%RMSD were still reported. This does not include joint work at the shoulder that reported a difference between an increased body segment inertia set at 11.4%RMSD. The over estimation of joint work during the ascent phase of the preparatory longswing is unknown as the joint power difference throughout the whole preparatory longswing is a minimal 2.1%RMSD.

5.4.2 Lab versus Field Analysis

The novel setup of a pseudo competition arena within a controlled lab environment allowed the comparison of data derived from indirect and direct methods. Differences between the automatic motion capture of joint coordinate data and digitised video data

increased as data was further differentiated to calculate joint work at the shoulder, hip and knee joints.

When comparing the differences between predicted bar forces calculated using IDA and joint coordinate data from the field and lab, differences increased to 9.8%RMSD in the horizontal and remained around 6.5%RMSD in the vertical. Kerwin and Hiley (2003) suggested that the errors associated with the accelerations derived from digitised data could lead to larger errors in the estimated forces using IDA, attributing to the increased difference in the horizontal joint forces. Maintaining a high degree of reliability in the digitising of joint centres would allow for reliable segment lengths and consequent segment accelerations for the computation of estimated joint and bar forces through IDA.

The CODA motion analysis system, compared to the 3D camera setup, had a sampling frequency four times greater at 200 Hz. It therefore was not unexpected to see that the CODA 200 Hz data had more oscillations than the video 50 Hz data when observing joint moment data due to the increase in precision. Although interpolated to 200 Hz, the video data was over smoothed with the interpolation occurring between two points as opposed to four. Random error due to the estimation of joint centres in every frame digitised as opposed to a fixed marker position in the CODA setup also provided natural smoothing within the video data.

The general wave form for the data from each method is similar but with approximately 22%RMSD for each of the joints, joint moments are considerably different when utilising lab and field based methods. With the consistency of differences between the two methods for all trials being relatively high (0.8%RMSD for shoulder and hip joint moments), differences in the system used as opposed to the process applied may explain the high differences. Previous authors have reported an increase in displacement accuracy of around 0.2% and angular displacement accuracy 4° when utilising motion analysis systems over video analysis systems (Ehara et al., 1995; Richards, 1999) highlighting systematic differences in the two approaches.

The hip joint moment values calculated in the current study were comparable to previous findings for the relative method used; automated motion analysis (Williams et al., 2011) and 3D video analysis (Arampatzis and Brüggemann, 2001; Kerwin and Irwin, 2010). Williams et al. (2011) reported a double peak hip joint moment utilising the CODA motion analysis system for an elite male longswing, similar to the present study. The second peak joint moment at an approximate circle angle of 310° had the same relative value (1.4 kg/Nm) as the current study. Although the first peak was at a similar circle angle (260°),

the estimated joint moment in the current study was considerably largely (1.6 kg/Nm) compared to Williams et al. (2011) (0.7 kg/Nm). The differences between male and female longswing techniques and the differences in equipment (inclusion of low bar and decrease in stiffness for the women's uneven bars) should be considered when observing these differences in the second quarter of the longswing. Previous reports of hip joint moments calculated from digitised data for the female longswing by Arampatzis and Brüggemann (2001) and Kerwin and Irwin (2010) compared more favourably to the current study. Peak hip joint moments for all three studies occurred at an approximate circle angle of 280° and ranged between 2.75 (Arampatzis and Brüggemann, 2001) and 2.9 kg/Nm (Kerwin and Irwin, 2010).

Shoulder joint moments did not compare as well with previous 3D video studies (Witten et al., 1996; Arampatzis and Brüggemann, 2001; Kerwin and Irwin, 2010) with peak shoulder joint moments occurring around a similar circle angle (280°) but not similar in magnitude. Peak values ranged from 2.0 kg/Nm (Witten et al., 1996) to 10.7 kg/Nm (Kerwin and Irwin, 2010) with the current study reporting 4.8 kg/Nm. The current study investigated both the preparatory and general longswing whereas Witten et al. (2006) investigated the general longswing and Kerwin and Irwin (2010) the preparatory longswing preceding the Tkachev. The differences in joint moments at the shoulder may be a result of the following skill performed after the analysed longswing and the required contribution of the shoulder joint.

Consistency in joint power differences between CODA and 3D video methods decreased with a standard deviation of up to 8.8%RMSD. This suggests that the addition of angular velocity data to the joint moment calculation causes an increase in random error in the digitised data. Repeated digitisations produced differences in joint coordinate data of less than 1.3%RMSD but this increased to 5.1%RMSD at the shoulder, 3.6%RMSD at the hip and 8.9%RMSD at the knee when calculating joint angular velocities. Digitising error may therefore contribute substantially to the differences in joint powers between CODA and 3D video data sets (up to 29.4%RMSD). Bezodis (2006) also found large errors in joint power calculations when investigating uncertainties of IDA in sprinting. The influence of re-digitising the movement data on hip joint power was up to 41.2%RMSD, with the more dynamic nature of sprinting exceeding that of the preparatory longswing. Bartlett (2014) stated that higher sampling frequencies may also reduce errors in velocity and acceleration data. This may provide further explanation to the large differences found between the 200 Hz CODA data and the 50 Hz 3D video data. Peak joint powers in particular should be

reported with caution when utilising digitised coordinate data. The current study calculated peak joint power at the shoulder almost two times greater than Kerwin and Irwin (2010) and over six times greater at the hip. However, when comparing to the results of Arampatzis and Brüggemann (2001), the peak powers at the shoulder and hip joints were not so disparate. Around similar circle angles Arampatzis and Brüggemann (2001) reported 9.66 W/kg at the shoulder and 15.14 W/kg at the hip compared to 7.27 W/kg and 19.88 W/kg respectively in the current study.

Differences in joint power were further accentuated when integrated over a specified time period to calculate joint work. However, with joint power being over and under calculated inconsistency across the three joints, joint work differences were also inconsistent. Joint power at the hip for example was largely over calculated compared to the CODA dataset which increased the overall area under the curve (work done) and contributed to the large difference of 40.4%RMSD. Joint power at the knee however both over and under calculated joint power and therefore the difference between CODA and 3D video was only slightly higher than joint power at the knee at 23.6%RMSD.

Early work of Gervais (1993) reported a 22% difference between indirect IDA calculations for bar force and known directly measured bar forces. Kerwin and Hiley (2003) later improved on this by utilising the linear displacement of the high bar using video analysis. Kerwin and Hiley (2003) reported a 7% difference between directly measured bar forces and predicted bar forces. In the current study, directly measured bar forces compared to estimated bar forces from inverse dynamic analyses and the digitised joint coordinates, estimated horizontal and vertical bar forces to within 11.6 and 10.5%RMSD respectively. With the large differences of field of view considered between the current study (7.5 m) and Kerwin and Hiley (2003) (2.0 m) the difference between predicted and measured appears acceptable. Kerwin and Irwin (2006) reported that the IDA approach to predicting bar force was acceptable for determining the overall magnitude and force profile of the longswing on high bar. With this in mind it is important to take caution when reporting predicted bar force values, particularly at peak force, however identifying events such as a pull on the bar by the gymnast could be clearly identified. The temporal characteristics of reported events could also be key in determining differences in technique.

Williams et al. (2013) stated that the accuracy of a biomechanical analysis can be largely dependent on the method used to approximate the body's true anatomical structure. Earlier, Kwon (1996) commented that regardless of the method's accuracy, body segment inertia parameters are influenced by the estimation method chosen by the investigator. However,

these authors also illustrated the need of indirect methods stating the limitations of direct methods such as high cost, radiation exposure, complexity and lack of onsite facilities (Kwon, 1996).

Gittoes et al. (2009) evaluated a non-invasive method of collating anthropometric data from whole body images and found that inputting anthropometric measurement from whole body images to Yeadon's (1990) inertia model predicted whole body mass to within 2.9%. Utilising the image based approach the current study calculated total body mass within 4.1% of the gymnast's total body mass, within the range of error found by Gittoes et al. (2009) and on par with the between digitiser comparison of Atack et al. (2009). Challis and Kerwin (1996) reported that a well estimated volume and appropriate density values would allow for an accurate mass calculation, supporting the current error value. Although considered a successful alternative to direct measurement inputs, the influence of the image based method on the inputs to inverse dynamics had not been compared to other indirect methods. Kerwin and Irwin (2010) utilised the scaled customised inertia parameters approach based on a data set of junior national gymnasts. Similarly to Kerwin and Irwin (2010) the gymnast from the current study was matched as close as possible to a gymnast of similar mass from the database (93%). The comparison between the two indirect methods used in the laboratory and elite competition reported differences of less than 0.7%RMSD for joint centre locations. Bar force data differences increased but were still less than 2.0%RMSD, with the scaling approach predicting maximum bar forces to be lower than the image method. The trend of the scaling method predicting lower peak values than the image approach was also apparent when looking at the joint moment data. Differences between the two methods ranged from 7.2%RMSD at the shoulder and 4.0%RMSD at the hip. Williams et al. (2013) revealed a strong correlation between the subject mass and whether their predicted mass was over or under estimated using the Gittoes et al. (2009) approach. These authors found that a mass less than 71 kg was likely to be underestimated. If this finding was also present within the current study, an underestimated mass value could contribute to the over predicted peak joint moment data when compared to the scaling approach.

Joint power differences between the two BSIP approaches at the shoulder and hip joints increased marginally with the addition of angular velocity. Joint work however varied considerably more at the shoulder with the scaled approach over estimating by 31.1%RMSD. Similarly to the sensitivity analysis of different inertia profiles, joint power

calculation at the shoulder was a lower 7.1%RMSD and therefore with a standard deviation of 12%RMSD, variability across the trials could be the reasoning for this large difference.

In addition to the report made by Challis and Kerwin (1996) regarding the possibility of an appropriate mass estimation, Challis (1996) found that two different methods of calculating segmental moment of inertia did not have a large effect on the resultant joint moments. With previous research suggesting limited influence of changes in segment mass calculation and moment of inertia, centre of mass location appears to be an underlying influence of errors associated with body segment inertia parameters. This further emphasises the importance of accurate kinematic values.

5.5 Conclusion

Chapter 5 aimed to evaluate the robustness of inverse dynamics analyses and the errors associated when applied to the female longswing on the uneven bars through a sensitivity analysis. A second aim was to examine the influence of lab and field based methods on the calculated joint kinetics and the consequent mechanical findings. From previous research it is known that there are errors associated with inverse dynamics (Challis and Kerwin, 1996) and when collecting data in the field (Elliott and Anderson, 2007), therefore an evaluation of the methods proposed is highly valuable.

Building on from the previous research of Challis and Kerwin (1996), a sensitivity analysis was employed and found that changes in kinematic inputs to IDA influenced joint kinetic data considerably. By perturbing cut off frequency 1 Hz below and 1.5 Hz above the selected cut off frequency, less than a 0.7%RMSD in positional data resulted in up to 6.5%RMSD for joint moments, power and work. Similarly when looking at joint centre location, approximately a 1.3%RMSD for coordinate data between re-digitised trials increased up to 12.1%RMSD for joint kinetic data. These findings highlight the valuable importance of a comprehensive residual analysis prior to data analysis and the influence of the selected cut off frequency on the acceleration derivatives over the positional.

Comparing lab and field based methods revealed key influences of the kinematic data collection on the joint kinetic data. With the CODA motion analysis having four times the temporal resolution, the joint moment data from the 3D video setup appeared smoother and with less oscillations, even with interpolation. The difference in sampling frequencies may therefore attribute to the large differences in the joint kinetic data. When comparing peak joint moments with previous literature using the same relative methods, hip joint moments

compared favourably to those previously reported. Digitised data were particularly similar with 0.15 kg/Nm separating Arampatzis and Brüggemann (2001), Kerwin and Irwin (2010) and the current study for similar movements.

Throughout the sensitivity and lab versus field analysis, the hip joint was consistently the least affected by the comparative parameters and methods. The hip joint is paramount to distinguishing the three distinct longswing techniques identified in Chapter 3 and throughout the thesis. Moving forward to the subsequent chapter, differences in joint kinetics between the three longswing techniques greater than the errors found in the current chapter could be expected at the hip joint in particular. Caution should be taken when reporting peak values in the joint kinetics due to the over and under estimation at this point in the preparatory longswing in particular. Differences in the sensitivity of input variables and between the different methods of collection were highlighted at these points and therefore the temporal characteristics and overall magnitude of joint kinetic variables should take precedence over peak magnitude in the analysis.

Through Method Validation (Theme 3), it is evident that there are errors associated with the indirect methods proposed for the subsequent chapter. However, with ample care taken in processing the kinematic data and the subsequent analysis these should be kept to a minimum. Theme 4 and 5 (Biomechanical Musculoskeletal Approach and Biomechanical Energetics Approach) will be a principal part to the thesis in determining the importance of technique selection and providing explanation to the underlying movement patterns executed in the straddle Tkachev preparatory longswing.

CHAPTER SIX

KINETIC AND ENERGETIC ANALYSES OF LONGSWING TECHNIQUES PRECEDING THE STRADDLE TKACHEV

6.1 Introduction

Key techniques for the longswing preceding the performance of the Tkachev on uneven bars were identified from elite competition data collected at Olympic and World Championships in Chapter 3. The three techniques of the longswing identified included the arch, straddle and pike. Angular momentum and joint angular kinematic differences between the three distinct longswing techniques preceding the straddle Tkachev were reported in Chapter 4. However, differences were not apparent at the point of release and therefore reasons for one technique being selected over another not clear (Manning et al., 2011). Yeadon and Hiley (2000) reported that the location of shoulder and hip extension and flexion throughout the circle angle of the longswing may be a result of the gymnast's strength or muscular effort that they had to endure to perform the backward longswing. A joint kinetic analysis would provide an explanation of the kinematic differences found in Chapter 4 and explain why one longswing technique may be more advantageous than another from a musculoskeletal perspective. Kinetic analyses aid in determining the muscular demands placed on the performer which is important in the development of the skill (Kerwin and Irwin, 2010) and the coaching applied (Kopp and Reid, 1980). Irwin and Kerwin (2007) highlighted the importance of the similarity between preparatory activities and the demands of the final skill, working towards a more effective coaching process. Therefore it would be beneficial to determine any differences in the kinetics and energetic demands of varying longswing techniques to allow coaches to tailor training to these demands.

Utilising world class competition data provided innovation and an increase in knowledge of the contribution to elite performance in Women's Artistic Gymnastics. Prior to examining joint kinetics in the field, Chapter 5 provided confidence in the indirect method of approach and evaluated the methods applied to field based data. Joint kinetic data were sensitive to changes in the kinematic data highlighting the importance of the noise removal technique and as such a comprehensive residual analysis in order to maintain confidence in the kinetic output. The comparison of kinetic data collected in the field and lab environment highlighted the systematic differences in the two methods. When comparing

joint kinetics to previous research that utilised the same field based methods, high levels of confidence were maintained (Arampatzis and Brüggemann, 2001; Kerwin and Irwin, 2010). The findings from Chapter 5 have provided a level of confidence and knowledge of the influence of the inputs into IDA and the effect on field based data, with the temporal characteristics and overall magnitude of joint kinetic variables taking precedence over estimated peak values.

Previous research has built on from kinematic analyses of the backward longswing and examined the kinetic characteristics of the key joints including the shoulder, hip and knee joints as well as forces at the bar (Kopp and Reid, 1980; Witten et al., 1996; Arampatzis and Brüggemann, 1998; Irwin and Kerwin, 2006; 2007; Kerwin and Irwin, 2010). Insight into the mechanical demands of varying techniques to perform the same skill however has not been addressed and could therefore increase a coach's knowledge and understanding for more applicable skill and coaching development for different techniques.

The mechanical demand placed on the performer can be defined by the mechanical work required of the gymnast to complete the skill successfully. The total joint work done contributes to the gymnast-bar energy system and is the mechanical energy the gymnast is inputting into the system through muscular action. The shift in the analysis to an energetics one provides a more holistic view of the biomechanical energetic processes involved in the effective performances of these skills, which has previously been used successfully (Arampatzis and Brüggemann, 1998; 1999; 2001; Irwin and Kerwin, 2007; Kerwin and Irwin, 2010).

The energetic relationship between gymnast and high bar has been further investigated with researchers identifying the need for muscular work from the gymnast to overcome a loss in mechanical energy (Okamoto, 1987; Witten et al., 1996; Arampatzis and Brüggemann, 1998; 1999; 2001; Irwin and Kerwin, 2006; Kerwin and Irwin, 2007; 2010). Temporal characteristics of the shoulder and hip joint actions have been of particular focus in determining the efficiency of utilising the potential of the high bar characteristics; elasticity and strain energy (Witten et al., 1996; Arampatzis and Brüggemann, 2001; Irwin and Kerwin, 2006). The energetic approach of Arampatzis and Brüggemann (2001) identified that gymnasts transferred energy into the high bar through actions at the shoulders and hips in the downswing of the preceding longswing. However, the decrease in total gymnast energy was not equal to the increase in bar energy inferring a loss of energy in the downswing, resulting in more work required during the ascent phase and a greater demand placed on the gymnast (Irwin and Kerwin, 2006). The differences found

previously in Chapter 4 in shoulder and hip kinematics and functional phase characteristics could potentially be explained by the energetic processes of the three distinct longswing techniques and the demand of each technique. Coaches and scientists would be provided with new information that would recognise the potential of each longswing within the skill development process as well as the selection of physical preparation activities that best suit particular techniques.

The aim of Chapter 6 was to investigate the underlying kinetics of three varying longswing techniques preceding the straddle Tkachev and to examine the biomechanical energetic input from the gymnast to the gymnast-high bar energy system. With the overall thesis aim of increasing knowledge and understanding of the biomechanics underpinning varying longswing techniques for the determination of effective technique selection, Chapter 6 founded an effectiveness score of varying longswing techniques in an attempt to provide reasoning for differences in technique. In order to achieve the above aim, the following research questions were addressed:

- How do joint kinetics vary during changes in preparatory longswing technique preceding the straddle Tkachev?
- How do energetic inputs from the gymnast vary for different longswing techniques and is one longswing technique considered more effective than another?

Through a Biomechanical Musculoskeletal Approach (Theme 4) and Biomechanical Energetic Approach (Theme 5), the overall purpose of this chapter was to develop a greater understanding of how the varying movement patterns of each longswing technique are executed and whether one technique may be more demanding than another. Building on from the previous kinematic analyses and validation of field based methods, quantification of the kinetic and energetic characteristics of three distinct longswing techniques will provide coaches and scientists with new knowledge and understanding that may be vital to the skill development of more complex skills and the selected coaching process.

6.2 Method

Participant and data collection information was previously reported in Chapter 4 where the same protocol was taken. Therefore the methodology will only be summarised here but is fully detailed in Chapter 4 section 4.2.1 and 4.2.2.

6.2.1 Participants

Eighteen successfully executed straddle Tkachevs from the qualification rounds of the Sydney 2000 Olympic Games and Stuttgart 2007 World Championships were selected. Each straddle Tkachev was categorised by the longswing technique preceding it and the height and mass of the six gymnasts within each group recorded; arch (age 15.5 ± 0.8 years, height 1.47 ± 0.07 m, mass 39.0 ± 5.6 kg), straddle (age 18.8 ± 3.6 years, height 1.49 ± 0.05 m, mass 40.4 ± 6.6 kg) and pike (age 17.8 ± 1.5 years, height 1.55 ± 0.06 m, mass 45.7 ± 3.9 kg).

6.2.2 Data Collection

Calibration and movement images were collected from two video cameras operated at 50 Hz. Calibration at the Sydney 2000 Olympic Games comprised of a three dimensional volume encompassing the uneven bars (3.0 m x 4.3 m x 3.5 m). A single calibration pole consisting of five equally-spaced spheres (0.1 m diameter) of known coordinates was sequentially placed at six pre-measured positions providing 30 known locations within the field of view. The 2007 World Championship performances were calibrated using two static (1.0 m x 1.0 m x 3.0 m) cuboids giving 48 known coordinates and a calibration volume 2.0 m x 3.7 m x 3.0 m. The origin was defined as the centre of the high bar in its neutral bar position with the calibrated volume encompassing the analysed preparatory longswing.

6.2.3 Data Processing

PEAK Motus software (Vicon Peak 9.0, UK) was used to digitise both the calibration and movement images from the two international competitions. Calibration images were digitised for 10 frames from each camera view and subsequently averaged. Movement images consisted of the preceding longswing 20 frames before the horizontal to 20 frames after re-grasp of the Tkachev. 20 frames before the horizontal on the descent phase of the longswing ensured 135° was included within the digitised movement image and accommodated for the subsequent noise reduction technique. 135° was the specified circle angle for all trials due to it being after the gymnast had completed the preceding skill and before the gymnast initiated either the shoulder or hip functional phases (Manning et al., 2011).

The centre of the high bar, the gymnast's head, right and left wrist, lateral epicondyle of the elbow, estimated centre of rotation of the glenohumeral joint, greater trochanter, lateral femoral condyle, lateral malleolus and fifth metatarsophalangeal were digitised for each

movement frame from each camera view. The data sets from both cameras were time synchronised using the methods of Yeadon and King (1999). A 12-parameter three-dimensional direct linear transformation (Marzan and Karara, 1975) was used to reconstruct the 3D coordinate data using the TARGET high-resolution motion analysis system (Kerwin, 1995).

The reconstructed coordinate data were filtered at a cut off frequency of 6 Hz using a Butterworth low-pass digital filter based on Winter's residual analysis (Winter, 2009) which fell within the boundary of cut off frequencies examined in Chapter 5. Residuals were calculated from 0 Hz to 20 Hz for the horizontal and vertical joint centre locations of the wrist, elbow, shoulder, hip, knee and ankle (Appendix II).

Yeadon's geometric model (1990) was used to define the gymnasts' centre of mass with gymnast limb length from the digitised data, height and mass combined with Yeadon's mass ratio correction factor. Segment centre of mass were derived from calculating the distance of the centre of mass from the proximal end of each segment.

Circle angle was defined as a vector from the gymnast's centre of mass to the neutral position of the bar. Circle angle was defined as previously reported with 90° being when the gymnast was in a handstand position on top of the bar and 450° when the gymnast returned to handstand in an anti-clockwise, full rotation about the bar. All data were interpolated to 101 points using a cubic spline function (Mathcad 14, Parametric Technology Corporation, USA). To allow for comparison between gymnasts, the percentage circle angle was calculated between a circle angle of 135° to release.

6.2.4 Data Analysis

All data were analysed using a customised Mathcad (Kerwin, 2013. Mathcad 14, Parametric Technology Corporation, USA) programme. With bilateral symmetry assumed (Irwin and Kerwin, 2001) a four segment planar representation of the gymnast was constructed by averaging the raw coordinate data for the left and right side of the body. The model consisted of arm (hands, forearms and upper arms), trunk (including head and neck), thigh and shank (including feet) segments. To take into account for any out of plane movement, for example abduction at the legs in the straddle technique, an inertia scale correction factor was included within the customised Mathcad programme. The abduction of the legs in the straddle longswing, together with the reconstructed four segment model of the gymnast, required the inertia values of the lower limbs (thigh and shank) to be scaled to the new average length. To determine the influence of the inertia scale factor on

kinetic and energetic outputs, Root Mean Square Difference (RMSD) and percentage Root Mean Square Difference (%RMSD) for the inertia scale conditions were calculated (Appendix IV) with each RMSD being divided by the range of the non-scaled measurement and expressed as a percentage (Equation 6.1 and 6.2).

$$RMSD = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (x_{no\ scale} - x_{scaled})^2}$$

[6.1]

RMSD = root mean square difference

n = number of samples

$x_{no\ scale}$ = *data point without inertia scale factor*

x_{scaled} = *data point with inertia scale factor*

$$\%RMSD = \frac{RMSD}{Max_{original} - Min_{original}} \times 100$$

[6.2]

%RMSD = percentage root mean square difference

$Max_{original}$ = *Maximum data point without inertia scale factor*

$Min_{original}$ = *Minimum data point without inertia scale factor*

6.2.4.1 Joint Kinetics

As detailed in 5.2.4.1, a two dimensional inverse dynamic analysis was conducted to calculate the internal joint forces and moments at the knees, hips, shoulders and high bar. Known zero forces at the toes were combined with Newton's second law of linear motion (Equation 6.3) to calculate net joint forces. Horizontal and vertical forces acting at each joint were calculated from the mass and acceleration of each segment and the force transferred from the preceding segment (Equations 6.4 and 6.5). Linear acceleration of each segment was calculated by differentiation of the positional data.

$$\sum F = m \cdot a$$

[6.3]

F =linear force acting on segment

m = mass of segment

a = linear acceleration of segment

$$IJFy_i = m_i \cdot ay_i - IJFy_{i-1} \qquad [6.4]$$

IFy = horizontal internal joint force

ay = horizontal acceleration of segment

$$IJFz_i = m_i \cdot az_i - IJFz_{i-1} - m_i \cdot g \qquad [6.5]$$

IFz = vertical internal joint force

ay = vertical acceleration of segment

g = acceleration due to gravity

Newton's second law of angular motion was utilised to calculate joint moments at the knees, hips and shoulders (Equation 6.6). Internal joint forces acting at a known distance from the segment's centre of mass and distal/proximal end of the segment, together with resultant joint moments, angular acceleration and segment moment of inertia were denoted. Angular acceleration of each segment was calculated by differentiation of the angle data.

$$JM_i = (IJFz_i \cdot pro_y) + (IJFy_i \cdot pro_z) + (IJFz_{i-1} \cdot dis_y) + (IJFy_{i-1} \cdot dis_z) + I_i \cdot \alpha_i - JM_{i-1}$$

$$[6.6]$$

JM = net joint moment

y = horizontal direction

z = vertical direction

pro = distance between the CM and the proximal end of the segment

dis = distance between the CM and the distal end of the segment

I = moment of inertia of segment

α = angular acceleration of segment

Joint powers at the shoulder, hip and knee joints were calculated as the product of the previously defined joint moment and angular velocity (Equation 6.7).

$$JP_i = JM_i \cdot \omega_i \qquad\qquad [6.7]$$

JP = net joint power

JM = net joint moment

ω = joint angular velocity

i = ith segment

Joint moment and joint angular velocity values were utilised to determine the nature of the muscle action occurring around the joint centre. Defined functionally, flexion at all joints was defined as positive with the joint angle increasing and therefore a positive joint angular velocity. With the joint moment occurring in the same direction, a positive joint power was represented as a concentric action and therefore closing of the respective joint. A concentric action, positive joint power, can also occur during a negative joint moment and negative angular velocity, however closing of the respective joint occurs. When the joint's angular velocity and joint moment were in opposing directions, a negative joint power was distinguished by an eccentric action and a possible opening of the joint. Figure 6.1 below illustrates how the two parameters, joint moment and joint angular velocity determined the direction of joint power and therefore the muscle action characteristic.

		ω	
		+	-
JM	+	+JP	-JP
	-	-JP	+JP

Figure 6.1. Determination of the direction of joint power and the surrounding muscle action.

Joint work at the shoulders, hips and knees was calculated using equation (Equation 6.8) below, the time integral of joint power.

$$JW_i = \int_{t1}^{t2} JP_i \cdot dt$$

[6.8]

JW = net joint work

JP = net joint power

t = time

Total work was calculated as the sum of work done at the shoulder, hip and knee joints (Equation 6.9).

$$JW_{total} = \sum JP_i \cdot dt$$

[6.9]

JW$_{total}$ = net total joint work

Work contribution of the shoulder, hip and knee joints were calculated as a percentage of the total work done by each of the gymnasts. Joint moment, power and work values were subsequently normalised by gymnast height and body mass through a modified scaling procedure by Hof (1996) allowing for comparisons between longswing techniques (Equations 6.10, 6.11 and 6.12).

$$JMn_i = \frac{JM_i}{m \cdot g \cdot h}$$

[6.10]

$$JPn_i = \frac{JP_i}{m \cdot g^{3/2} \cdot h^{1/2}}$$

[6.11]

$$JWn_i = \frac{JW_i}{m \cdot g \cdot h}$$

[6.12]

JMn = normalised net joint moment

JPn = normalised net joint power

JWn = normalised net joint work

j = jth joint

m = mass of participant

g = acceleration due to gravity

h = height of participant

6.2.4.2 Functional Phase Joint Kinetics

Chapter 4 identified significant differences in the functional phase characteristics of the three varying longswing techniques, in particular the start of the shoulder and hip functional phases. Figure 6.2 below illustrates the first and second shoulder (SFP1 and SFP2) and hip (HFP1 and HFP2) functional phases.
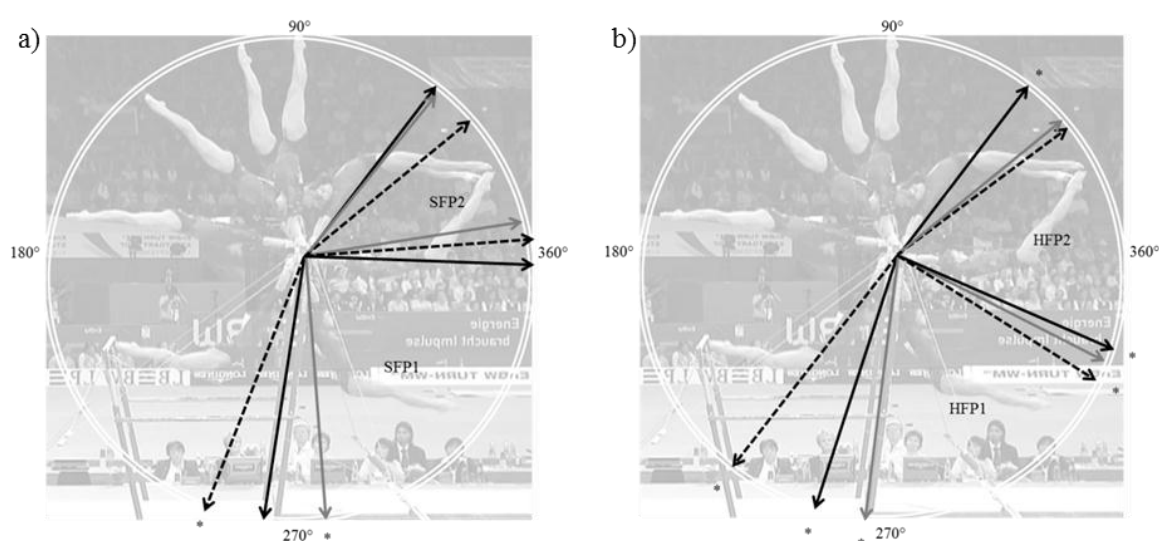
Figure 6.2. Example of a) shoulder (SFP) and b) hip (HFP) functional phases (1 and 2) for the arch (dashed), straddle (black) and pike (grey) longswing. * denotes significant difference (p ≤ 0.05)

Data were interpolated to 101 points between the start and end of the respective functional phases to allow for a functional phase percentage (Mathcad 14, Parametric Technology Corporation, USA). Bar forces and shoulder and hip joint kinetics within their respective interpolated functional phases were then reported. Total joint work and joint energetics were interpolated to the combined functional phase of the shoulder and hip joint; the earliest initiation and latest conclusion (often coinciding with release).

6.2.4.3 Biomechanical Energetics

Total joint work done at the shoulders, hips and knees represented the energy transferred from the gymnast's musculoskeletal system to the total energy system. Gymnast energy is one of the three components used in calculating the total energy within the gymnast-high

bar system which comprises of angular kinetic energy, gravitational potential energy and linear kinetic energy (Equation 6.13).

$$E_{total} = \frac{1}{2} I\omega^2 + m \cdot g \cdot h + \frac{1}{2} mv^2$$

[6.13]

E_{total} = total energy

I = moment of inertia of mass centre

ω = angular velocity of mass centre

m = mass

g = acceleration due to gravity

h = height

v = linear velocity

Equation 6.13 has been adapted below, modelled as a series of segments (Equation 6.14) as opposed to the gymnast's whole body (Equation 6.13). Following the work of Smith (1975) a sensitivity analysis was conducted in order to determine the influence of modelling the gymnast as a single rigid body or as a four segment model on joint energetics of the longswing preceding the straddle Tkachev (Appendix V).

$$E_{total} = \sum \frac{1}{2} I_i \omega_i^2 + \sum m_i \cdot g_i \cdot h_i + \sum \frac{1}{2} m_i v_i^2$$

[6.14]

Total energy was normalised by the method of Hof (1996) to account for the varying mass and height values across the different longswing techniques (Equation 6.15).

$$En_{total} = \frac{E_{total}}{m \cdot g \cdot h}$$

[6.15]

En_{total} = normalised total energy

To estimate a level of effectiveness for each longswing technique, the increase or decrease in total energy was calculated by subtracting the total energy at the start of the longswing (135°) from the total energy at the end (release) (Equation 6.16). The change in total energy was then calculated as a percentage of the change in gymnast total energy (Equation 6.17) in order to determine the musculoskeletal demand on the performer and its contribution to the gymnast-bar energy system (Equation 6.18).

$$\Delta E_{total} = E_{total\ end} - E_{total\ start} \qquad [6.16]$$

$E_{total\ end}$ = total energy at release
$E_{total\ start}$ = total energy at a circle angle of 135°

$$\Delta E_{gym} = E_{gym\ end} - E_{gym\ start} \qquad [6.17]$$

E_{gym} = gymnast total energy
$E_{gym\ end}$ = gymnast total energy at release
$E_{gym\ start}$ = gymnast total energy at a circle angle of 135°

$$ES = \frac{\Delta E_{total}}{\Delta E_{gym}} \ x \ 100$$

$$[6.18]$$

ES = effectiveness score

6.2.5 Statistical Analysis

Differences between discrete variables for the arch, straddle and pike longswing techniques were quantified using an Analysis of Variance (ANOVA). In order to meet the assumptions of the ANOVA, tests for normality (Shapiro-Wilkes) and homogeneity of variance (Levene's test) with the alpha level set to $p \leq 0.05$ were carried out. To establish the meaningfulness of these data effect size was also reported as a d score (Cohen, 1988) and interpreted using Hopkins (2002) complete scale (< 0.2 trivial, $0.2 - 0.6$ small, $0.6 - 1.2$ moderate, $1.2 - 2.0$ large, $2.0 - 4.0$ very large and > 4.0 perfect). This method has previously been used in Women's Artistic Gymnastics research (Manning et al., 2011;

Farana et al., 2013). To quantify the differences between continuous data sets for the three varying techniques, Root Mean Squared Difference (RMSD) and percentage RMSD (%RMSD) were determined (Equation 6.19). In order to calculate %RMSD, the pooled maximum and minimum values from all three longswing techniques (arch, straddle and pike) were used in calculating the dividing denominator.

$$\%RMSD = \frac{RMSD}{Max_{pooled} - Min_{pooled}} \times 100$$

[6.19]

Max$_{pooled}$ = Maximum pooled data point

Min$_{pooled}$ = Minimum pooled data point

6.3 Results

The following results section is structured into three parts; joint kinetics, functional phase joint kinetics and biomechanical energetics. The influence of the inertia scale factor and the segmental total energy calculation on joint kinetics and energetics were further detailed in Appendices IV and V. Subsequently, joint kinetics, functional phase joint kinetics and biomechanical energetics of the three longswing techniques were reported in order to address the overall aim of increasing knowledge and understanding of the biomechanics underpinning varying longswing techniques for the determination of effective technique selection.

6.3.1 Joint Kinetics

Estimated bar force profiles (Fb) were similar between the three longswing techniques (Figure 6.3) but differed at peak force in terms of magnitude and time ($p \leq 0.05$). In the initial 50% of the preceding long as the gymnast passed the low bar and pulled on the high bar, horizontal bar force was the same for all three techniques. However, the physical pull on the high bar by the gymnast and the increase in horizontal force was significantly lower and delayed in the pike longswing ($p \leq 0.05$). The second pull on the high bar during the ascending phase of the skill just prior to release was significantly different ($p \leq 0.05$) in the arch technique. At approximately 65% through the longswing the straddle and pike technique executed a significant pull on the high bar ($p \leq 0.05$) with the arch technique producing a horizontal bar force 25% less. In the remaining 10% of the longswing the arch technique matched the horizontal force of 2.5 BW illustrated earlier by the straddle and

pike techniques but at the significantly later time (Figure 6.3a). The similarity in the straddle and pike techniques compared to the arch is further highlighted in Table 6.1 with a 5.8%RMSD compared to 10.6%RMSD and 12.9%RMSD respectively.

For two thirds of the preparatory longswing, all three longswing techniques shared a similar vertical bar force profile (0-33 and 66-100%). The time and magnitude of peak vertical force however varied significantly ($p \leq 0.05$) with the arch technique producing the greatest peak vertical force. The straddle and pike were 83% and 89% of their arch counterpart respectively and occurred at an earlier circle angle approximately 45% through the longswing compared to 55%.
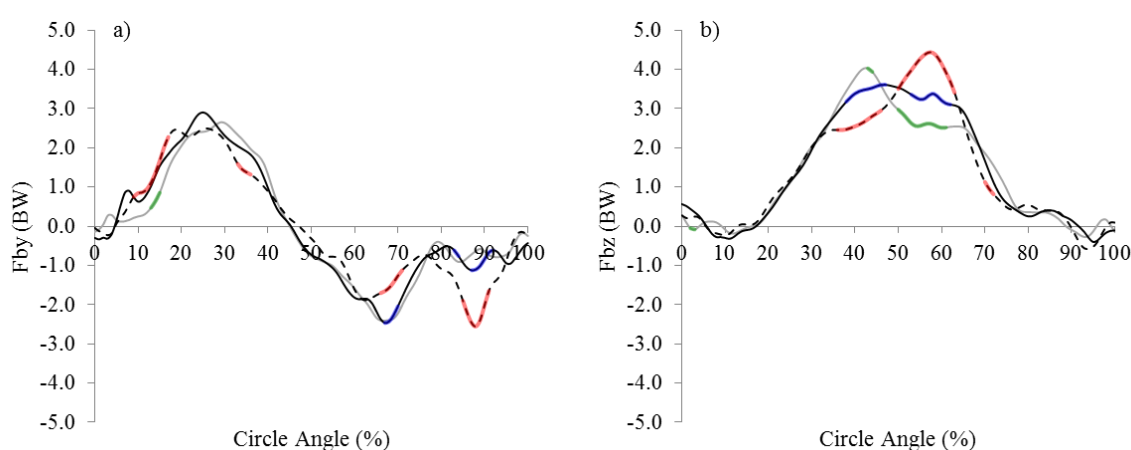
Figure 6.3. Mean normalised horizontal (a) and vertical (b) predicted bar forces for the arch (dashed), straddle (black) and pike (light) longswing with significant differences ($p \leq 0.05$) between the arch and pike (red), straddle and arch (blue) and pike and straddle (green) illustrated by the coloured lines.

Joint moments at the shoulder, hip and knee joints between the three distinct longswing techniques varied most on the descent phase of the longswing and at the instant of peak joint moments. For the remaining 35% of the longswing prior to release the joint moment profiles for each of the techniques continued similarly with differences mainly in the temporal characteristics (Figure 6.4).

A key observation in the shoulder joint moment profiles (Figure 6.4a) was the magnitude of peak shoulder moment in the arch longswing closing the shoulder joint compared to the other two techniques. The peak joint moment produced at the shoulder in the straddle and pike technique was approximately 60% of the peak value produced in the arch equivalent, reporting a large effect size (d score = 1.5). Joint moments at the shoulder joint were

relatively varied across the three longswing techniques as the gymnasts negotiated the low bar, as highlighted by %RMSD values between 13.9%RMSD and 17.0%RMSD (Table 6.1). During the ascent phase, a negative shoulder moment as the gymnasts opened their shoulder angle occurred around 80% of the completed longswing for each technique with a final positive peak moment occurring just before release (Figure 6.4a). The pike technique in this final 5% of the longswing had a greater joint moment than the arch and straddle illustrating a final contribution from the shoulder at release through shoulder joint extension.

Table 6.1. RMSD and %RMSD for normalised joint kinetics of the three distinct longswing techniques preceding the straddle Tkachev from a circle angle of 135° to release

	Arch Vs Straddle		Arch Vs Pike		Straddle Vs Pike	
	RMSD	%RMSD	RMSD	%RMSD	RMSD	%RMSD
Fyb	0.54	10.6	0.66	12.9	0.29	5.8
Fzb	0.47	10.8	0.70	15.8	0.32	7.3
JMn_{shd}	0.04	13.9	0.05	17.0	0.04	14.3
JMn_{hip}	0.03	14.1	0.05	22.4	0.04	17.0
JMn_{kne}	0.01	13.9	0.01	18.5	0.01	14.9
JPn_{shd}	0.15	12.6	0.22	18.5	0.19	15.7
JPn_{hip}	0.18	15.7	0.25	22.1	0.23	20.5
JPn_{kne}	0.04	26.2	0.04	27.3	0.03	20.1
JWn_{shd}	0.03	41.1	0.04	64.0	0.02	28.7
JWn_{hip}	0.02	7.7	0.06	22.7	0.05	20.8
JWn_{kne}	0.00	12.1	0.01	19.7	0.00	15.5

Joint moments at the hip were significantly different between the three longswing techniques ($p \leq 0.05$) as the gymnasts passed the low bar (between 10 and 35% of the completed longswing). The different movement patterns distinguishing the three techniques were executed by different joint moments at the hip, with the extension of the arch longswing demonstrated by a negative hip moment and the flexion of the pike longswing a positive hip moment. The location of peak hip joint moment was at a similar point in the longswing for each of the three techniques (approximately 60% through the longswing) with the arch longswing executing a significantly larger ($p \leq 0.05$) peak hip moment (27% greater).

As the gymnasts across all three longswing techniques approached release they performed similar characteristics of negative hip moments, however gymnasts performing the pike longswing initiated this hip extension earlier than the arch and straddle counterparts (Figure 6.4b). The pike longswing followed this with a significantly earlier positive hip moment ($p \leq 0.05$) and flexion at the hip than the straddle longswing.
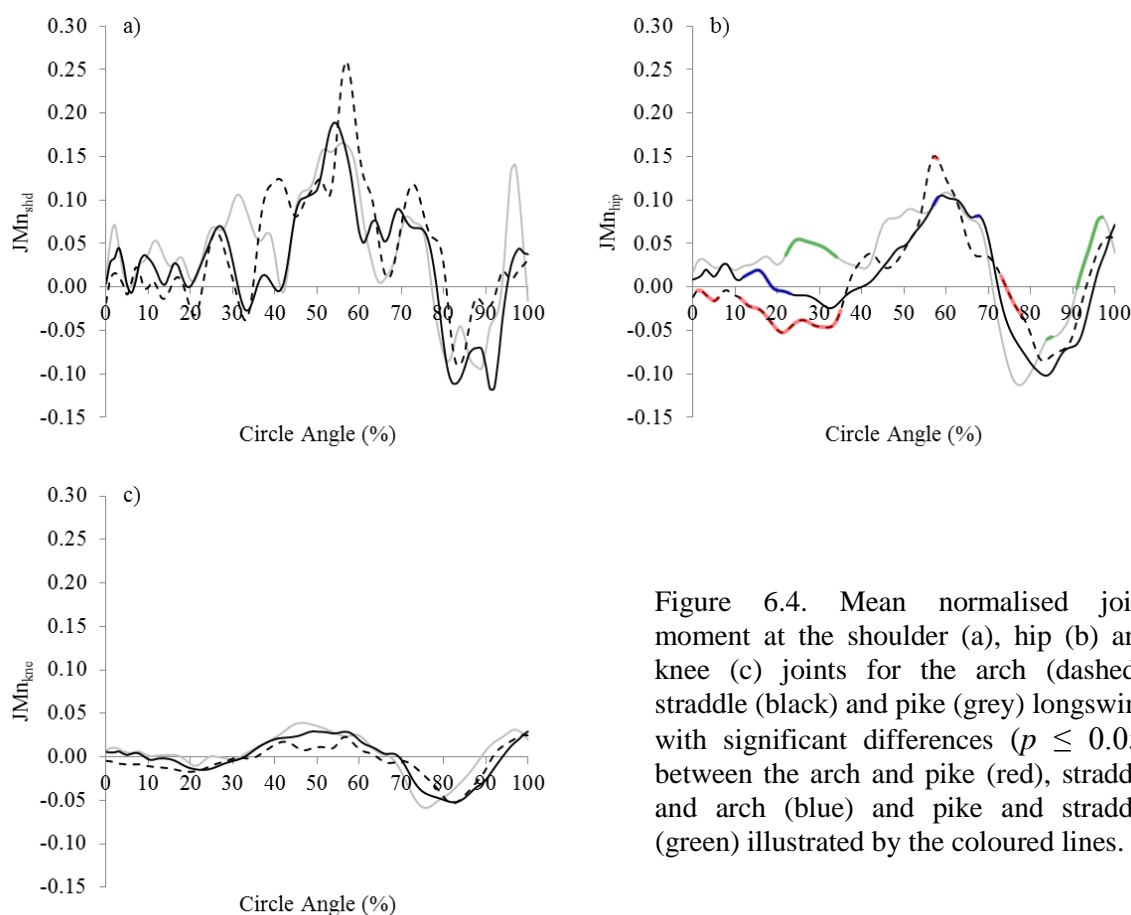
Figure 6.4. Mean normalised joint moment at the shoulder (a), hip (b) and knee (c) joints for the arch (dashed), straddle (black) and pike (grey) longswing with significant differences ($p \leq 0.05$) between the arch and pike (red), straddle and arch (blue) and pike and straddle (green) illustrated by the coloured lines.

Continuous knee joint moment profiles for each of the three techniques were similar with no significant differences ($p \geq 0.05$) or large effect size. Knee joint moments followed a similar pattern to that of the hip joint with a peak joint moment approximately 50% through the longswing and then a negative peak moment prior to release, with the pike longswing initiating the knee extension approximately 5% earlier than the arch and straddle techniques.

Average shoulder joint power fluctuated for each of the three longswing techniques as the gymnast passed the low bar, with no significant contribution from the shoulder joint occurring until 40% through the longswing. At 40% the arch longswing initiated a larger peak power than the straddle and pike techniques that did not increase in shoulder joint power until 50% of the way through the longswing (Figure 6.5a). An earlier and greater

concentric action from the arch longswing contributed to the closing of the shoulder joint. Prior to release the pike technique executed a larger negative joint power than the other two variants. The positive joint moment combined with the negative angular velocity highlighted the opening of the shoulder joint at release but with the requirement of the pike technique to emit a larger positive joint moment to ensure hyper flexion did not occur.
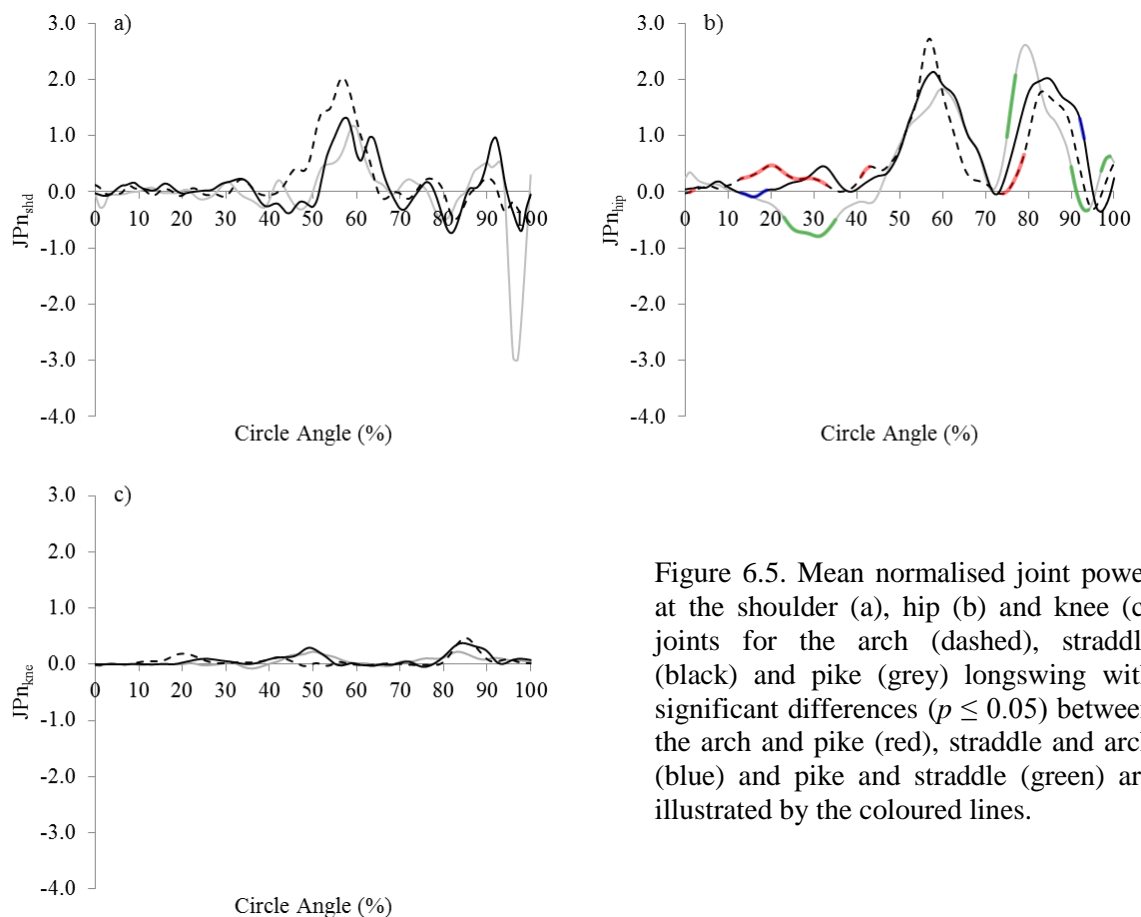
Figure 6.5. Mean normalised joint power at the shoulder (a), hip (b) and knee (c) joints for the arch (dashed), straddle (black) and pike (grey) longswing with significant differences ($p \leq 0.05$) between the arch and pike (red), straddle and arch (blue) and pike and straddle (green) are illustrated by the coloured lines.

When negotiating the low bar, significant differences were apparent in the hip joint power profiles similarly to the hip joint moments ($p \leq 0.05$). The key kinetic contrast at this point in the longswing was the negative hip power of the pike technique attempting to open the hip joint on the downswing compared to the positive hip powers of the other two variants, ensuring the hip joint did not hyper extend (Figure 6.5b).

The three longswing techniques all clearly illustrated two positive peaks in hip joint power throughout the preparatory longswing (Figure 6.5b). For the arch longswing the initial peak at approximately 60% through the completed longswing was 35% more than the second peak at 80%. This was reversed for the pike longswing with the initial power peak being 71% of the second peak. The straddle longswing generated two peak hip powers of similar

magnitude within 5% of each other. There were no significant differences reported between the three longswing techniques in the initial peak power contributing to the gymnasts closing their hip angle ($p \geq 0.05$). However, during the hip extension prior to release, the pike longswing extended significantly earlier than the arch and straddle longswing techniques ($p \leq 0.05$). This characteristic prior to release combined with the negative hip power when passing the low bar contributed to the high %RMSD values when concerning the pike technique (Table 6.1).
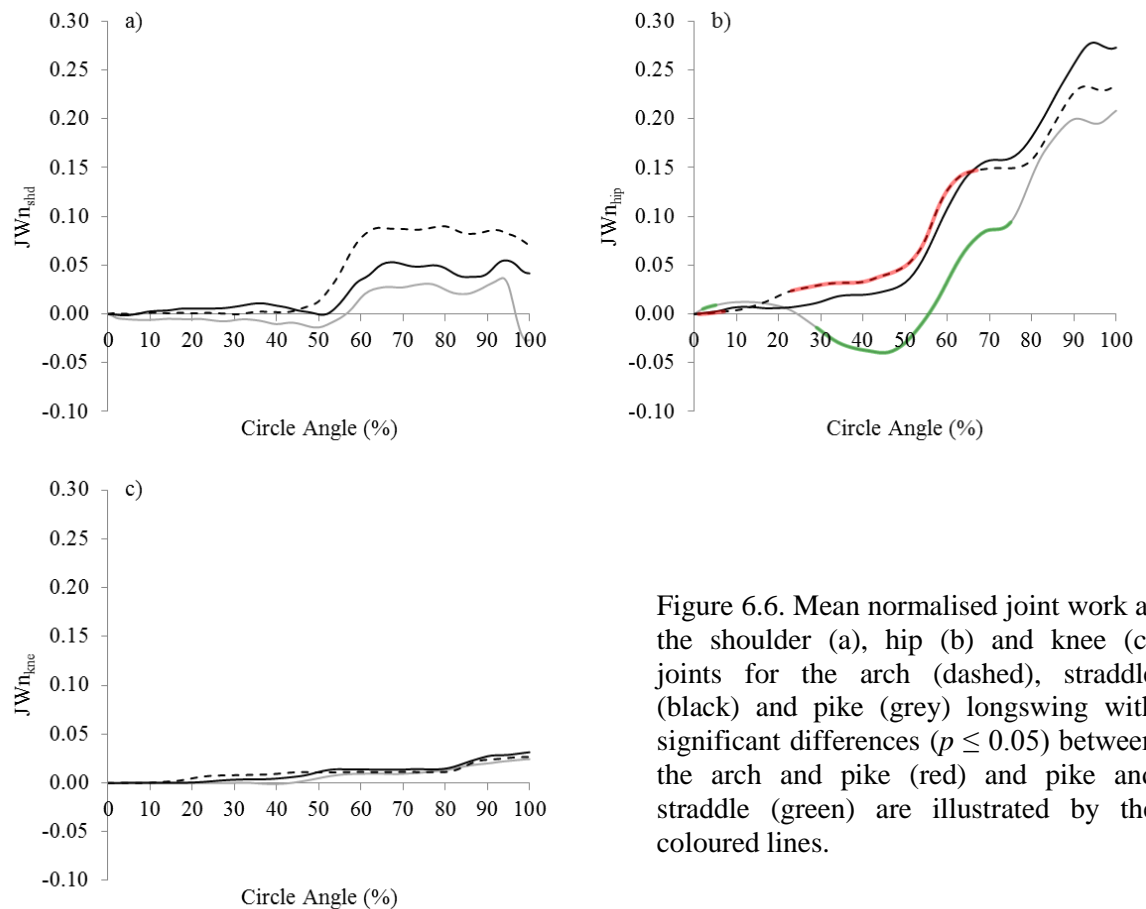
Figure 6.6. Mean normalised joint work at the shoulder (a), hip (b) and knee (c) joints for the arch (dashed), straddle (black) and pike (grey) longswing with significant differences ($p \leq 0.05$) between the arch and pike (red) and pike and straddle (green) are illustrated by the coloured lines.

Joint work at the shoulders appeared considerably different with %RMSD values of 64% between the arch and pike longswing techniques (Table 6.1). However, no significant or meaningful differences were reported due to high variability (Appendix VI). Although not significantly different ($p \geq 0.05$), interestingly the pike longswing was the only technique that reported negative joint work at the shoulder (Figure 6.6a) which occurred in the first 50% of the longswing.

Negative joint work at the hip joint was another key characteristic of the pike longswing before the gymnast reached the bottom of the longswing at 270°. During the ascent phase

all three techniques illustrated positive work with two rapid increases at approximately 50% and 75% of longswing completion. Joint work at the hip joint was significantly less in the pike longswing ($p \leq 0.05$) during the first increase in joint work (around 50% of the completed longswing) which corresponds to peak joint moment and power at the hip.
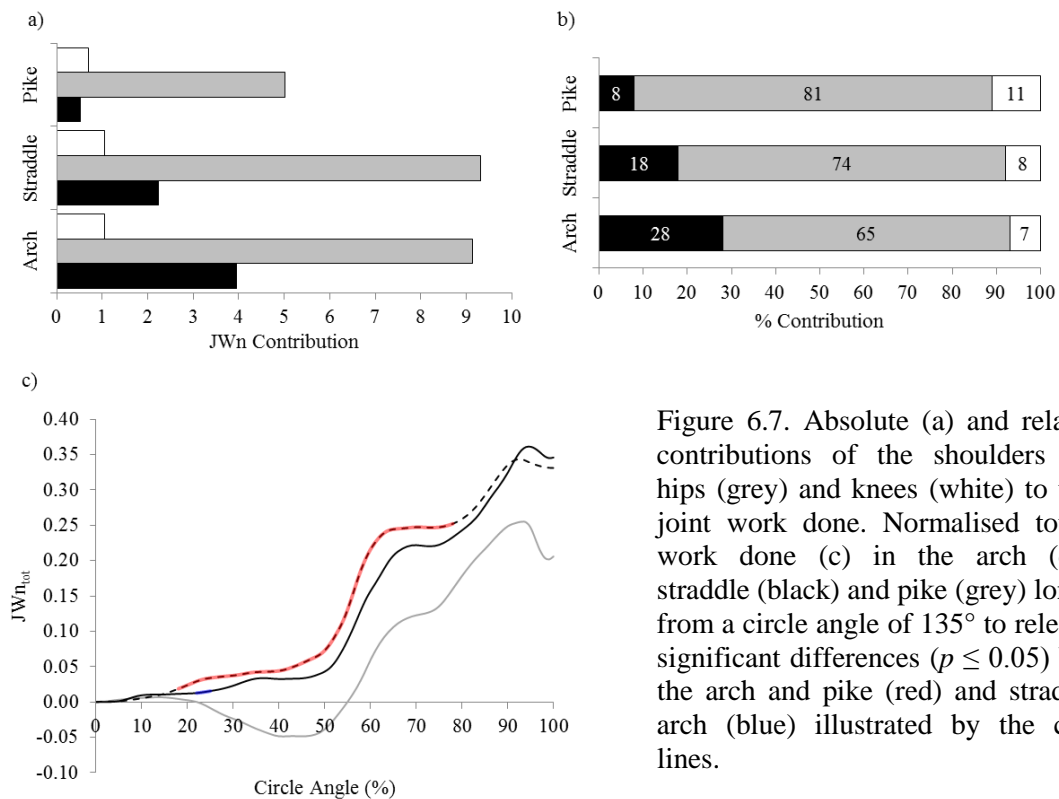
Figure 6.7. Absolute (a) and relative (b) contributions of the shoulders (black), hips (grey) and knees (white) to the total joint work done. Normalised total joint work done (c) in the arch (dashed), straddle (black) and pike (grey) longswing from a circle angle of 135° to release with significant differences ($p \leq 0.05$) between the arch and pike (red) and straddle and arch (blue) illustrated by the coloured lines.

Joint work generated at the hips was the largest contributor to total joint work for all three techniques contributing 65%, 74% and 81% to the arch, straddle and pike longswing respectively (Figure 6.7b). Although the hip joints contributed the most in the pike longswing, total joint work at the hips was 45% less than the arch and straddle techniques. Twenty eight per cent of the total work done in the arch longswing was contributed by the shoulder joints with the same joint accounting for 18% of total joint work done in the straddle variant. The shoulders contributed 8% of total work done for the pike longswing which was 87% and 77% less than the arch and straddle variants respectively.

Figure 6.7c illustrates the total joint work done in the three longswing techniques and the significant difference between the arch and pike techniques. The first 50% of the pike longswing was significantly different to the arch technique ($p \leq 0.05$) due to the negative work contribution from the shoulders and hips in the pike technique. The remaining

significant difference between these two techniques imitated that of the hip joint due to the significant contribution to total joint work.

Of the total joint work done in the arch and straddle longswing, over 92% and 81% was positive work at the shoulders, hips and knees respectively. For the pike longswing however, negative work at the shoulders, hips and knees contributed 40%, 14% and 12% respectively (Table 6.2). The negative joint work in the pike swing occurred prior to the gymnast reaching a circle angle of 270° and therefore as the gymnast had to negotiate the low bar. The amount of negative work contributed by the hips at this point was significantly different to the other two longswing techniques ($p \leq 0.05$).

Table 6.2. Normalised joint work for the arch, straddle and pike longswing preceding the straddle Tkachev and percentage of positive/negative work done of total joint work. * denotes significant difference ($p \leq 0.05$)

	Shoulders			Hips			Knees		
	Arch	Straddle	Pike	Arch	Straddle	Pike	Arch	Straddle	Pike
Positive	4.11	2.46	1.36	9.21	9.32	5.92*	1.08	1.06	0.73
	(93%)	(81%)	(60%)	(100%)	(100%)	(86%)	(92%)	(100%)	(88%)
Negative	-0.16	-0.22	-0.84	-0.02	-0.00	-0.91*	-0.02	-0.00	-0.04
	(7%)	(19%)	(40%)	(0%)	(0%)	(14%)	(8%)	(0%)	(12%)

6.3.2 Functional Phase Joint Kinetics

Horizontal bar forces profiled against interpolated shoulder and hip functional phases remained significantly different between the arch and remaining two techniques. During the ascent phase the arch longswing was more aligned with the straddle and pike pull on the bar, however either side of the peak force the arch longswing emitted significantly less horizontal bar force (Figure 6.8a and 6.9a). The significantly later pull by the arch technique ($p \leq 0.05$) remained consistent during the shoulder and hip functional phases.

Predicted vertical bar force during the shoulder and hip functional phases concurred with the previous finding of the arch technique executing a significantly larger and later downward force on the bar ($p \leq 0.05$). Interestingly the peak vertical force for the straddle and pike techniques did not occur in either the shoulder or hip functional phases but prior to the gymnasts executing full shoulder flexion or hip extension.

There were limited significant differences between the three longswing techniques for joint moments at the shoulder during the shoulder functional phases. The only significant
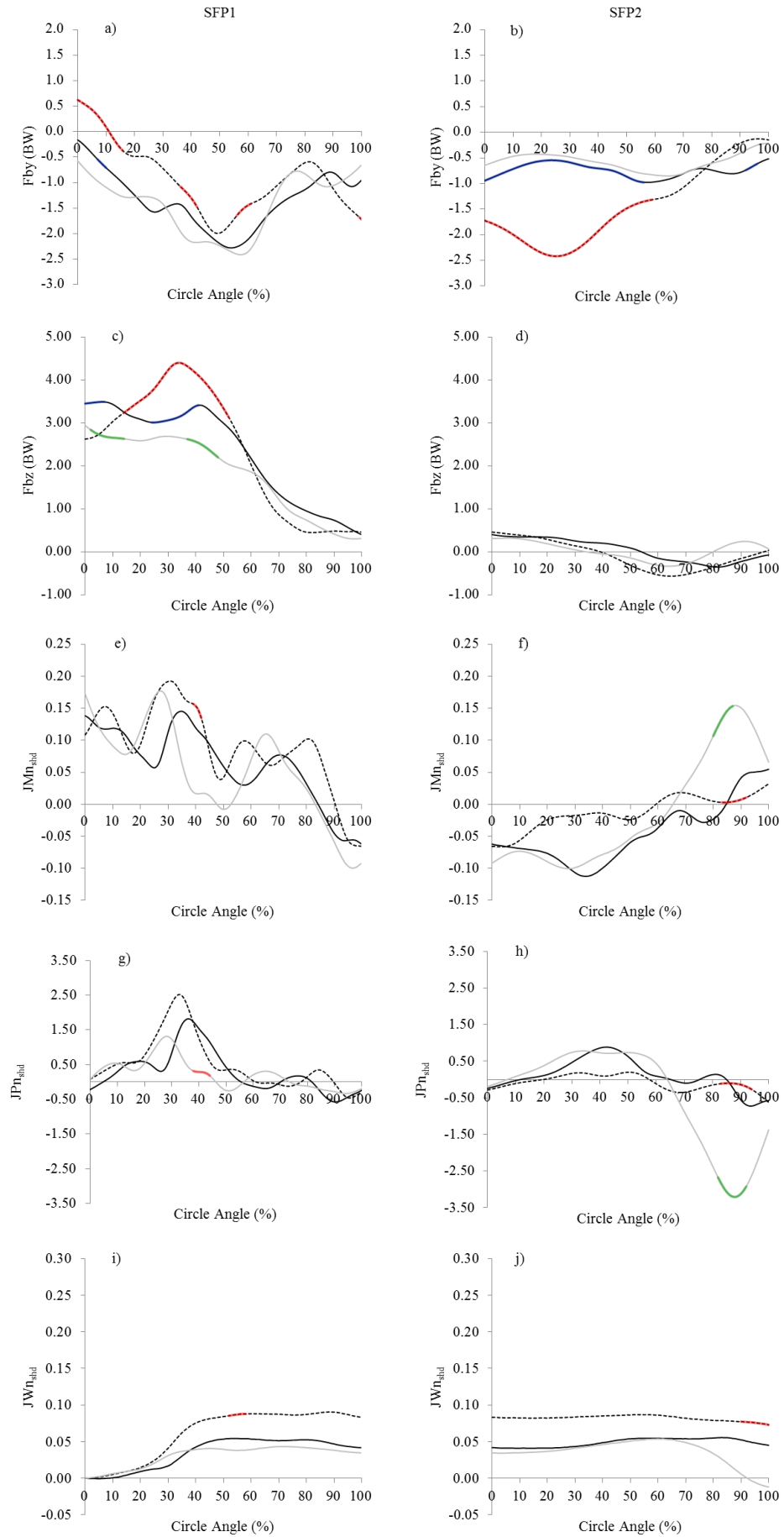
Figure 6.8. Mean normalised predicted bar force and shoulder joint kinetics during the first (SFP1) and second (SFP2) shoulder functional phase with significant differences ($p \leq 0.05$) between arch and pike (red), straddle and arch (blue) and pike and straddle (green) illustrated by coloured lines.
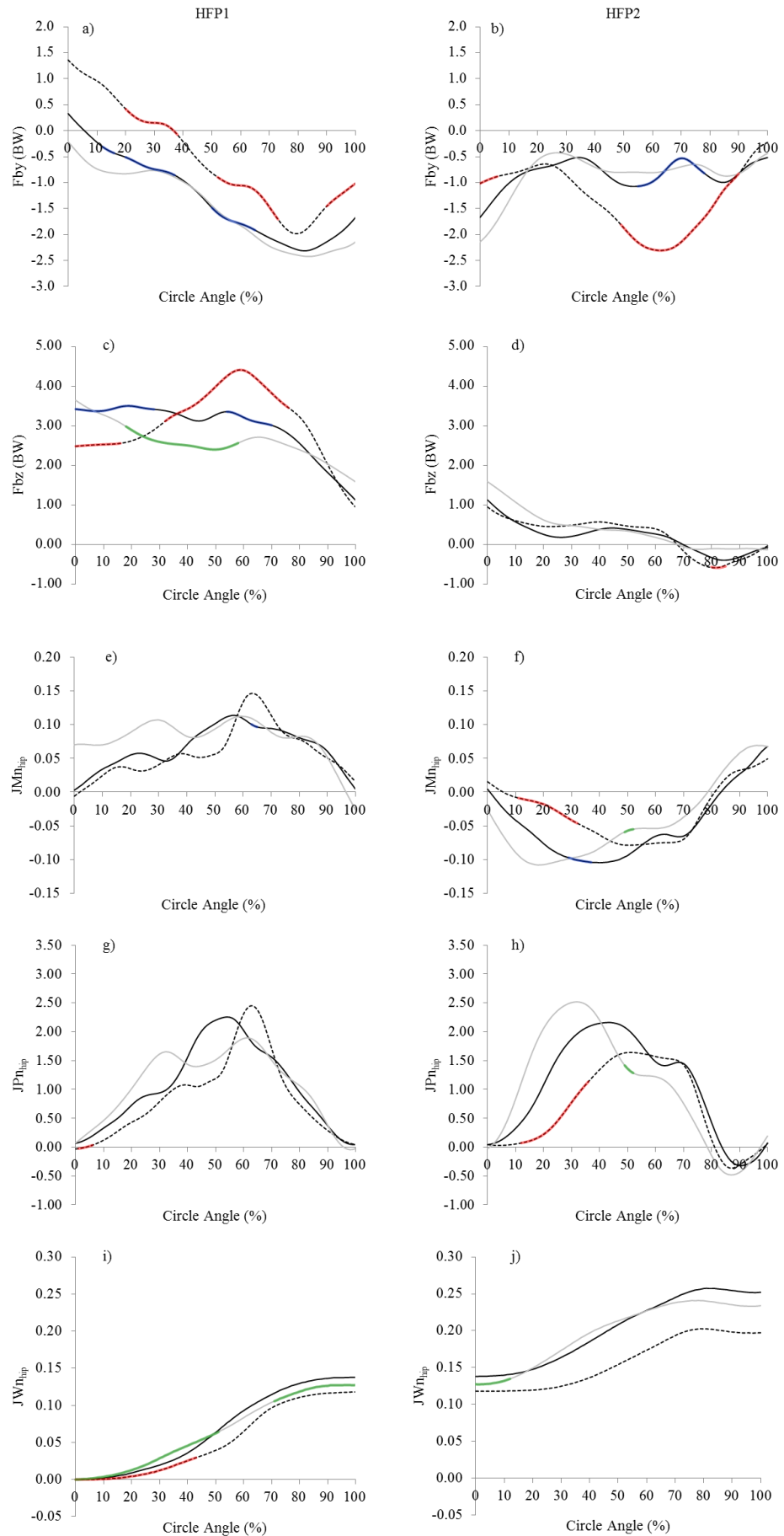
Figure 6.9. Mean normalised predicted bar force and hip joint kinetics during the first (HFP1) and second (HFP2) hip functional phase with significant differences ($p \leq 0.05$) between the arch and pike (red), straddle and arch (blue) and pike and straddle (green) illustrated by the coloured lines.

difference occurred in SFP2 for the pike longswing with a significantly larger ($p \leq 0.05$) joint moment prior to release (Figure 6.8f). The large contribution from the shoulder in the pike longswing was consistent with the interpolated longswing findings although not deemed significant.

Significant differences in hip joint moments reported during the interpolated longswing (135° to release) were not present in the interpolated hip functional phase data (Figure 6.9e). This was due to the hip functional phase for all three techniques starting from a circle angle of 263° and therefore after the gymnast had passed the low bar where there were key differences in technique. Peak hip moment in the arch longswing was significantly larger than the straddle ($p \leq 0.05$) but remained the only difference in HFP1. Similarly to joint moments at the shoulder, differences prior to release between the three techniques remained consistent when interpolated to the hip functional phase, with the addition of statistical significance (Figure 6.9f). The significantly larger joint moment in the pike longswing ($p \leq 0.05$) combined with angular velocity contributed to the significantly larger joint power at release in the pike longswing compared to the arch.

Differences in peak hip powers remained statistically insignificant ($p \geq 0.05$) when interpolated to the first hip functional phase during hip flexion on the upswing (Figure 6.9g). During hip extension and the concentric action at the hip joint prior to release, the pike longswing remained significantly earlier ($p \leq 0.05$) than the arch longswing but not than the straddle technique (Figure 6.9h).

Negative joint work at the shoulder and hip joints were omitted when considered in solely the shoulder and hip functional phases respectively. This finding highlights the influence of passing the low bar on the pike longswing. No significant differences ($p \geq 0.05$) were found in the shoulder functional phases for shoulder joint work, concurring with joint kinetic findings through a circle angle of 135° to release (Figure 6.8i and j). Hip joint characteristics however changed with a change in focus from the complete preparatory longswing to HFP1 and HFP2. Joint work at the hip in first 40% of HFP1 of the arch longswing was significantly lower ($p \leq 0.05$) than that of its pike counterpart (Figure 6.9i) which corresponded to a peak in joint power in the pike longswing. The straddle longswing was also significantly lower ($p \leq 0.05$) in this phase than the pike longswing. With the arch longswing producing the lowest joint work at the hip throughout HFP1 and HFP2, the straddle and pike techniques alternated in the technique producing the greatest joint work at the hip. The straddle longswing produced significantly more work ($p \leq 0.05$) than the

pike longswing between the first and second functional phases before they alternated twice more before release (although non significantly).

When looking at individual joint work contribution to total joint work throughout the combined shoulder and hip functional phases (Figure 6.10), the straddle longswing became similar to the pike technique as opposed to the arch technique when previously reported against the full circle angle. The absolute and relative contribution of the shoulder and hip joints for the straddle and pike techniques were within 5% and 2% of each other respectively. The amount of joint work contributed by the hip joint was greatest in the pike longswing and was 25% more than the hip joints in the arch longswing. Previously when considering the joint work contribution between a circle angle of 135° to release, the hip contribution in the arch longswing was 45% more than the pike longswing.

The percentage of hip contribution fluctuated by approximately 4% for each of the three longswing techniques when interpolated to the functional phases instead of 135° to release; with the pike longswing having a significantly greater contribution from the hip joint than the arch longswing ($p \leq 0.05$). The shoulder contribution increased in the arch and pike techniques by 8% with the knee contribution decreasing by approximately 5%. Although there were differences in the shoulder and hip contributions across the three longswing techniques, total joint work revealed no significant differences ($p \geq 0.05$) within the shoulder and hip functional phases (Figure 6.10c).
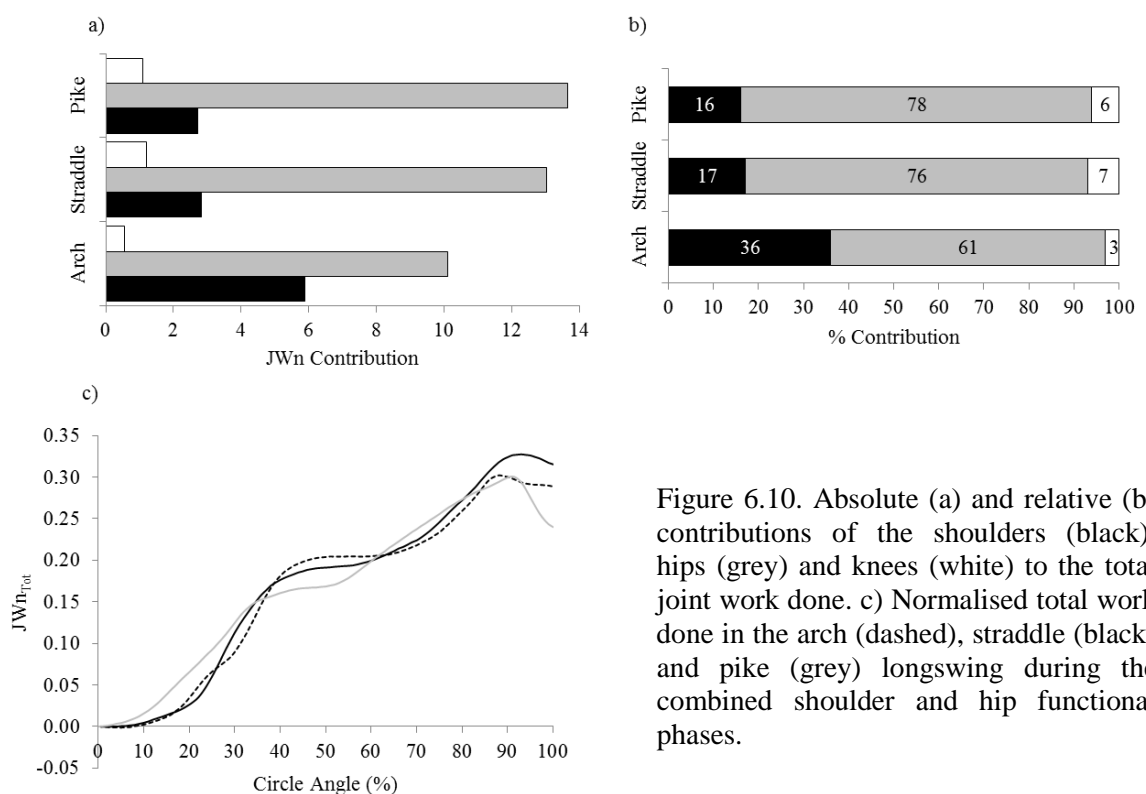
Figure 6.10. Absolute (a) and relative (b) contributions of the shoulders (black), hips (grey) and knees (white) to the total joint work done. c) Normalised total work done in the arch (dashed), straddle (black) and pike (grey) longswing during the combined shoulder and hip functional phases.

Key differences in positive and negative joint work at the shoulders, hips and knees when interpolated to the shoulder and hip functional phases were the decrease in negative work during the pike longswing. Negative work at the shoulders reduced to 23% from 40% and negative work at the hips was removed (0%). The arch longswing reported an increase in negative work at the knees joints whereas the straddle technique reported a 6% negative work increase at the shoulders (Table 6.3).

Table 6.3. Normalised joint work in the shoulder and hip functional phases for the arch, straddle and pike longswing and percentage of positive/negative work done of total joint work

	Shoulders			Hips			Knees		
	Arch	Straddle	Pike	Arch	Straddle	Pike	Arch	Straddle	Pike
Positive	5.97	3.40	3.22	10.16	13.06	13.64	0.63	1.22	1.12
	(98%)	(75%)	(77%)	(99%)	(100%)	(100%)	(83%)	(97%)	(88%)
Negative	-0.09	-0.58	-0.51	-0.05	-0.03	-0.00	-0.08	-0.02	-0.04
	(2%)	(25%)	(23%)	(1%)	(0%)	(0%)	(17%)	(3%)	(12%)

6.3.3 Biomechanical Energetics

To establish the effectiveness of each longswing technique, the increase in gymnast energy (total joint work) was expressed as a ratio of the increase in total energy. An increase in total energy to the gymnast-high bar system can only occur as a result of muscular work and therefore the effectiveness score allowed for the determination of the most effective longswing technique.

Figure 6.11 illustrates that for all three longswing techniques there was an increase in total energy during the longswing preceding the straddle Tkachev. Figure 6.11a illustrates that initially there was a decrease in total energy as the gymnasts passed the low bar and before they reached the bottom of the swing. The pike longswing had an earlier and greater loss in energy compared to the arch (47% significantly greater) and straddle variants which reached similar loss values (within 11%). Once the gymnasts passed underneath the bar all three techniques increased the total amount of energy above the amount of energy the gymnast-bar system possessed at a circle angle of 135°.

a)

b)

c)
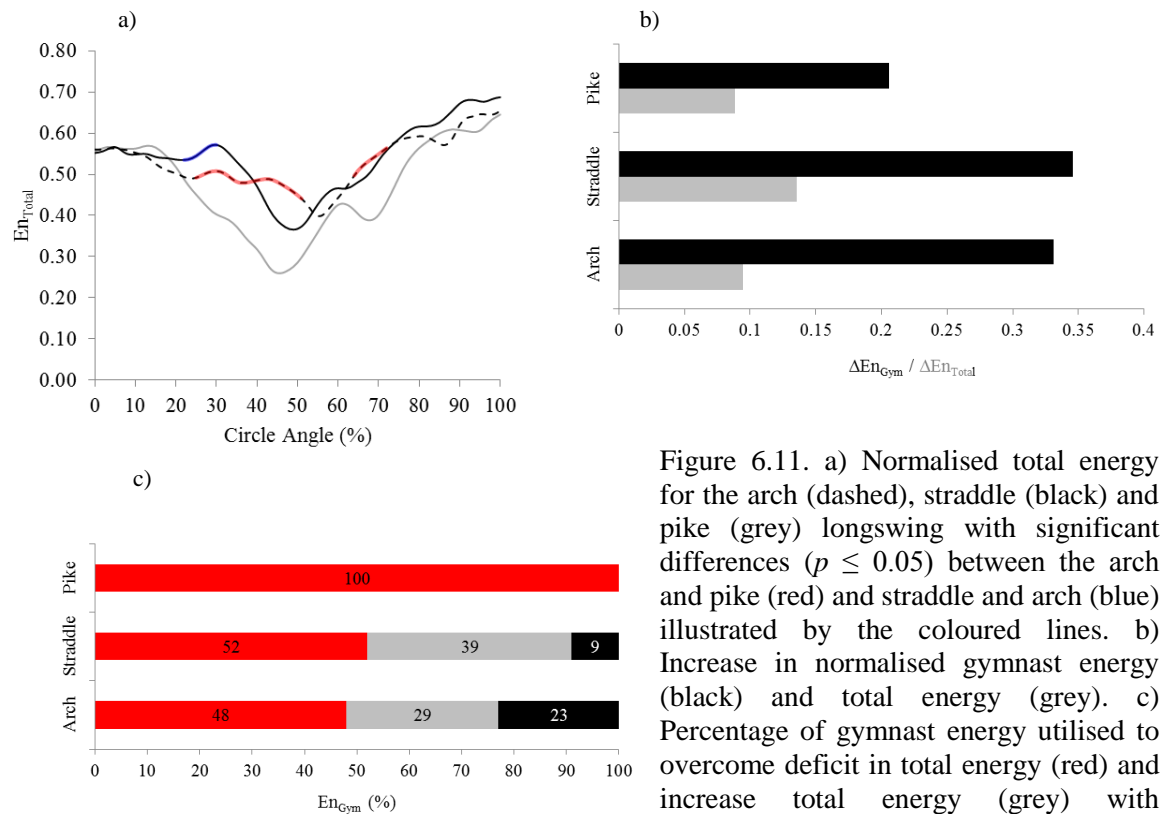
Figure 6.11. a) Normalised total energy for the arch (dashed), straddle (black) and pike (grey) longswing with significant differences ($p \leq 0.05$) between the arch and pike (red) and straddle and arch (blue) illustrated by the coloured lines. b) Increase in normalised gymnast energy (black) and total energy (grey). c) Percentage of gymnast energy utilised to overcome deficit in total energy (red) and increase total energy (grey) with remaining gymnast energy (black).

At approximately 70% of the completed longswing, the pike technique decreased in total energy compared to the other variants that increased. The arch longswing however did illustrate a similar decrease but at a later circle angle of 90% that coincides with the second pull on the high bar in the horizontal direction (Figure 6.3a). Total joint work (Figure 6.10c) contributed to the total energy of the gymnast-bar system in the form of gymnast energy. Figure 6.11b illustrates the increase in normalised gymnast energy between the three techniques (black bars) and the increase in normalised total energy from 135° to 405° (grey bars). The pike longswing noticeably had a lower increase in energy contribution from the gymnast but a similar increase in total energy as the arch longswing. Although the arch and straddle techniques had a similar increase in gymnast energy, within 4%, the increase in total energy was 30% less in the arch than the straddle, suggesting a loss of energy in the arch technique.

Expressed as a percentage (Figure 6.11c) the pike longswing utilised all of the change in gymnast energy to overcome the loss of energy in the first 50% of the longswing. The arch longswing contributed a smaller amount (29%) of their total gymnast energy than the straddle (39%) and pike longswing (43%) in order to increase the total energy of the gymnast-bar system and therefore appeared to have a greater amount of gymnast energy unused.
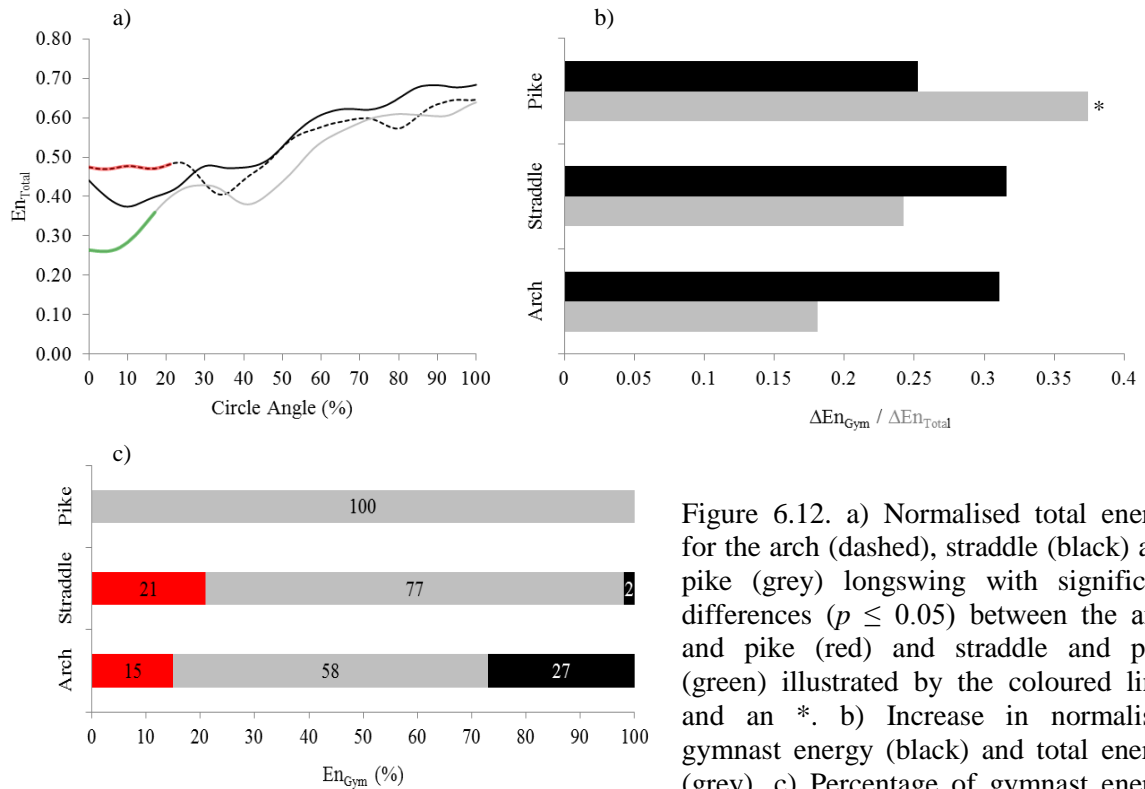
Figure 6.12. a) Normalised total energy for the arch (dashed), straddle (black) and pike (grey) longswing with significant differences ($p \leq 0.05$) between the arch and pike (red) and straddle and pike (green) illustrated by the coloured lines and an *. b) Increase in normalised gymnast energy (black) and total energy (grey). c) Percentage of gymnast energy utilised to overcome deficit in total energy (red) and increase total energy (grey) with remaining gymnast energy (black).

With focus on the combined shoulder and hip functional phase and the total gymnast-bar energy system, the pike longswing started with significantly less energy ($p \leq 0.05$) than its arch and straddle counterparts (Figure 6.12a). From approximately 25% of the completed functional phase, there was no difference between the three longswing techniques and total energy. The significantly lower starting energy of the pike longswing and the relatively similar release energy caused a significantly larger increase in total energy ($p \leq 0.05$) from the start of the functional phase to release in the pike. Although the increase in gymnast energy was up to 20% less than the arch and straddle techniques, the pike longswing utilised 100% of the total joint work to increase the total energy (Figure 6.12c). The arch and straddle longswing techniques had a similar increase in gymnast energy, however the arch technique only utilised 58% of this to generate a 25% lower increase in total energy compared to the straddle longswing; consequently leaving 27% unused.

6.4 Discussion

The aim of this study was to investigate the underlying kinetics of the varying longswing techniques preceding the straddle Tkachev and to examine any differences in biomechanical energetic input from the gymnasts. An increased understanding of the kinetics involved in varying longswing techniques provided insight into different physical demands required of the gymnast to complete this skill successfully utilising the most effective technique. Quantifying the physical demand of each longswing technique may attribute to the coaching and development of the straddle Tkachev by selecting physical preparation activities or a particular longswing technique that is best suited to a particular gymnast.

Performing the preparatory longswing preceding the straddle Tkachev one of three distinct ways made no significant difference to the release parameters of the skill (Manning et al., 2011). However, the significant differences identified in Chapter 4 in the functional phase characteristics may provide reasoning in terms of the muscular effort required of the gymnast in technique selection (Yeadon and Hiley, 2000).

The methods utilised within this study were previously validated in Chapter 5 to provide confidence in the kinetic and energetic findings reported. Differences between the field and lab based methods increased as data were further analysed from joint moments to joint work. Joint moment differences up to 24%RMSD were consistent across trials between the field and lab environment (1%RMSD) and were suggested as systematic differences and therefore a confidence in inverse dynamic analyses and joint moment data was obtained. Differences in joint power and work however had a lower consistency in difference across trials with the higher sampling frequency of CODA reducing the errors in velocity and acceleration data (Bartlett, 2014) and digitising error being key causes. Peak values should be taken with caution in the current study with temporal characteristics and overall magnitude of joint kinetics reported with a higher level of confidence.

Bar forces predicted in the current elite competition data compared favourably to previous work that has focused on the gymnast's interaction with the high bar (Kopp and Reid, 1980; Witten et al., 1996). Collecting data within a world renowned competition environment provided innovative and underrepresented data that required the iterative method of inverse dynamics analysis. Predicted peak horizontal bar forces within the current study were between 2.5 and 2.9 BW for each of the three longswing techniques. Supporting these values were the highly skilled female gymnasts within the work of Witten et al. (1996) who applied a peak horizontal force to the bar 2.6 times their body weight.

Contrasting to the similarity in the three longswing techniques in the downswing, during the upswing the arch longswing illustrated a double peak in horizontal force that differed considerably from the straddle and pike techniques. The second peak was of a similar magnitude (2.6 BW) to the straddle (2.5 BW) and pike (2.4 BW) but occurred at approximately 90% of the completed circle angle compared to 70%. Witten et al. (1996) reported a second peak in bar vertical force with the highly skilled gymnast suggesting a second pull on the bar at approximately 360° while the bar was recoiling. The differences in the direction of the force (horizontal versus vertical) between the two studies may be due to the difference in skills performed. Witten et al. (1996) investigated the kinetics of the general longswing whereas the pull on the bar in the current study may be explained by the release skill following the longswing and its requirement to travel backwards over the bar during the flight phase. The difference in skills may also explain the lower vertical force values (1.5 BW) from Witten et al. (1996) when compared to the current study. This finding implies to coaches and scientists that when a longswing technique is selected with the purpose of preceding a flight element, in this case the straddle Tkachev, the potential to interact more with the high bar may be beneficial knowledge for the selection process.

The location of maximum vertical force in the straddle and pike longswing was prior to the gymnast reaching the bottom of the longswing (43% and 47% respectively) with the arch longswing reaching peak vertical force at 57% of the completed circle angle. Gymnasts performing the arch technique concurred with Kopp and Reid (1980) who found that the maximum vertical bar force in the backward longswing appeared just after the gymnast had passed directly beneath the high bar (280-315°) and was approximately 3.5-3.7 times the gymnast's body weight. Witten et al. (1996) reported that producing maximum bar force at the bottom of the swing enabled greater bar deformation and therefore greater strain energy. The varying locations within the circle angle of peak vertical bar force provides insight into the interaction of the gymnast with the high bar and how gymnasts performing the arch longswing could potentially benefit from energy inputs from the bar during the ascent phase. However, efficiency of bar utilisation is also dependent on grip changes and the timing of change in body position (Witten et al., 1996).

Significant differences in joint moments at the hips were established between the three longswing techniques with the difference being primarily in the initial 40% of the completed longswing. The distinct longswing techniques were distinguished primarily by their movement pattern at the hip when negotiating passing the low bar in Chapter 3 and 4 and therefore this significant difference was not unexpected. Joint kinematics are clear

determents of identifying the varying longswing techniques, but kinetically their role is unknown. Witten et al. (1996) and Irwin and Kerwin (2006) identified the importance of the changes in body position through these joints in the efficiency of longswing technique and previous literature (Kopp and Reid, 1980; Witten et al., 1996; Arampatzis and Brüggemann, 1998; Irwin and Kerwin, 2006; 2007; Kerwin and Irwin, 2010) has examined the interaction of the shoulder, hip and knee joints and their contribution to the energy system of gymnast and bar.

The arch longswing demonstrated the highest peak moments at the shoulder and hip joints at the beginning of the ascent phase indicating a greater turning force when closing the shoulder and hip joints at the end of the first functional phases. The joint moments were highest at the shoulder joint, but with a lower positive angular velocity the peak shoulder power was less than that demonstrated by the hip joint (Irwin and Kerwin, 2006). Both joints combined positive joint moments and previously reported positive angular velocity highlighting the largest concentric action in the arch longswing out of the three longswing techniques. Preparatory activities focusing on the kick through concluding the first shoulder and hip functional phases should therefore be paramount in the conditioning of gymnasts executing the arch longswing. As the gymnasts performing the arch technique continued through the longswing, lower peak power values were established when compared to the other two variants, particularly at the hip joint. As the gymnast approached release, the negative angular velocity at the hip combined with the negative joint moment produced the lower positive peak power, eliciting a concentric action. The gymnast appears to be able to control the degree of hip extension in the second functional phase through a concentric action, but with a lower joint power and therefore lower demand on the gymnast; similarly to Kerwin and Irwin's (2010) finding. Building on the coaching perspective implied for the first hip functional phase, gymnasts performing the arch longswing may benefit from strength conditioning when focusing on hip extension physical preparation as opposed to maximising hip angular velocity.

Kerwin and Irwin (2010) compared the inward and outward Tkachev and in particularly the musculoskeletal demand placed on the performer when executing the variations in skill. The outward Tkachev was defined as the gymnast travelling towards the low bar during the flight phase whereas as the inward version travelled away from the low bar (Kerwin and Irwin, 2010). The above authors highlighted a difference in shoulder characteristics where joint moments at the shoulder reached a single larger peak in the outward Tkachev and smaller double peaks in the inward. In addressing the underlying

kinetics of the current study, the arch longswing has taken on the characteristics of the outward technique and the pike the characteristics of the inward Tkachev, contributing to a high effect size between the arch and pike techniques. When looking at the bar force data, the double peak in shoulder moment corresponds with the transition to negative horizontal force for the pike longswing, suggesting a pull on the high bar that isn't as smooth a transition and therefore effective as the arch technique.

A further difference was found between the arch and pike longswing techniques when investigating joint power at the shoulder. Similarly to the joint moment characteristics, the arch longswing resembles the outward Tkachev results of Kerwin and Irwin (2010) and the pike longswing the inward Tkachev. The large peak power at 55% of the circle angle indicates a large concentric action to close the shoulder joints as the gymnast enters the upswing in the arch longswing. This is similarly illustrated in the straddle and pike but of a smaller magnitude and delayed in the pike longswing. The pike longswing demonstrates a large negative second peak power just prior to release revealing a larger eccentric action in order to open the shoulder joints to go into the Tkachev. With the pike technique eliciting similar shoulder characteristics to the inward Tkachev of Kerwin and Irwin (2010), the pike longswing appears to be disadvantaged by the position of the low bar during the descent and the same influence of a low bar on the ascent. Coaches therefore could apply this new knowledge to their selection process by evaluating the reported disadvantageous kinetic characteristics of the pike longswing with traditional coaching practices that suggest the pike longswing is more suitable to taller gymnasts. As the gymnasts negotiated passing the low bar in the current study, significantly different demands were placed on the gymnasts executing varying longswing techniques. Performing the arch and straddle techniques required the gymnasts to initiate a slight concentric action at the hips to make sure the hip joints did not over extend on the downswing through passive kinetics (Yeadon and Hiley, 2000; Hiley and Yeadon, 2001). Contrastingly in the pike longswing, the hip joint had to act eccentrically to control the hip flexion and ensure the hip joints did not close too much on the downswing, as evidenced by the negative hip joint power between 20% and 40% of the completed circle angle.

When observing the joint power profiles at the hips, the arch longswing produced greatest hip power in the first functional phase (hip extension through to hip flexion) compared to the second functional phase (hip flexion through to hip extension) whereas the pike longswing had a lower initial peak compared to a higher second peak. Kerwin and Irwin (2010) similarly identified a double positive peak in hip power and established similar

musculoskeletal demand between varying techniques but a difference in distribution of joint power. The earlier initiation of the hip functional phase in the arch longswing may put a larger demand on the gymnast as the gymnast is attempting to flex at the hip joints while they are still travelling through the downswing of the skill compared to the pike longswing that does not initiate the hip functional phase until 31° later. During the second functional phase, both the arch and pike techniques had a second positive hip power peak combined of negative hip moment and negative angular velocity. With the arch longswing omitting the concentric action at a lower rate and magnitude (Figure 6.9h), the pike longswing appears to be under greater demand to control the hip extension prior to release before the hip joints act eccentrically at around 90% of the longswing.

Total joint work for each of the three longswing techniques illustrated a rapid increase in work done around a circle angle of 270° which equates to approximately 50% of the completed longswing, particularly at the shoulder and hip joints. Irwin and Kerwin (2006) similarly reported that the majority of the work done by the performer occurred during the ascent phase of the general longswing. At this key stage of the preparatory longswing, the gymnasts performing the arch longswing are able to generate significantly more work at the hip joints compared to the pike variant, possibly highlighting that the selection of this particular longswing technique would be better suited to gymnasts with high lower limb strength.

The hip joint is the dominant contributor to total joint work in all three longswing techniques; however the pike longswing contributed 45% less amount of work at the hip than the arch and straddle. The lower absolute value of joint work at the hips is due to there being no positive work contributed until the final 50% of the pike longswing compared to the arch and straddle contributing positively through 100% of the longswing. The contribution from the shoulder joints in the arch technique is double that of the straddle with the latter technique being double the amount of the pike longswing. Similarly to the hip joint, shoulder joint work in the pike longswing only transitions to positive work in the final 45% of the completed longswing. In negotiating the low bar during the downswing, the pike longswing contributes 40% and 14% negative joint work at the shoulders and hips respectively to the total joint work. The pike longswing therefore highlights the findings of Irwin and Kerwin (2006) and Sheets and Hubbard (2007) that minor changes in the hip and shoulder joints in order to negotiate the low bar can remove energy from a system; more than the arch and straddle techniques. Therefore, the kinematic differences established in Chapter 4 may be a result of the varying kinetic and energetic characteristics of different

longswing techniques. This finding emphasises the importance of technique selection and its influence on the energetic processes that precede the kinematic responses that are more apparent and visible to the naked eye of the coach.

Removing the varying temporal characteristics of the shoulder and hip functional phases (interpolating to functional phase as opposed to circle angle) removed significant differences in the predicted bar forces. Once the gymnasts passed underneath the high bar, the initial horizontal pull on the bar was initiated just after 50% of the completed longswing and was indifferent between the three longswing techniques. The second pull on the high bar remained in the arch longswing concluding that it was an additional characteristic of the arch techniques as opposed to a difference in timing. The arch longswing may therefore benefit from a more favourable trajectory travelling across the high bar with a significantly earlier release and high effect size with regard to horizontal velocity.

The arch longswing had a significantly greater vertical predicted bar force in the shoulder and hip functional phases however this may be due to the peak vertical bar force in the pike longswing not occurring in either of the functional phases. With only 73% and 90% of the peak vertical bar force in the pike shoulder and hip functional phases respectively, the bar deformation and therefore bar strain energy may be lower in the pike longswing (Witten et al., 1996) putting the gymnast in a less advantageous position for release than the other two techniques. Witten et al. (1996) stated that peak vertical bar force should be at the bottom of the longswing to enable maximum bar deformation, but with differences in functional phase location, maximum bar force occurs with the gymnasts in varying longswing positions. Peak vertical bar force in the arch longswing occurred significantly later than the other two techniques and as a result was in a dished position with flexion at the hips and extension at the shoulders as the bar was recoiling. The pike longswing had the earliest onset of peak vertical force prior to the shoulder and hip functional phases and therefore the gymnast was not in full shoulder flexion and hip extension as the bar was already recoiling. This may suggest the gymnast had to work harder in order to move through the functional phase and to keep up with the movement at the bar at the same time with the gymnast still descending with the bar moving upwards. The arch longswing was more synchronised with the high bar movements, ascending in the upswing as the high bar was also moving upwards, implying a positive interaction with the apparatus.

The influence of the shoulder functional phase on the shoulder joint moments highlighted the pike longswing prior to release. Joint moments at the shoulder were significantly

greater ($p \leq 0.05$) as the pike longswing opened the shoulder angle for release. With the shoulder functional phases aligned, the negative peak power in the pike longswing was also significantly greater than the arch and straddle techniques. The pike longswing was required to work harder eccentrically in order to open the shoulder angle and as a result the shoulder angle was more extended than the straddle longswing and put the gymnast in a favourable position in order to travel over the high bar.

Positive joint moments at the hips remained the same for all three techniques during the first hip functional phase but the negative turning force was initiated significantly earlier in the straddle and pike techniques compared to the arch. The extending peak power in the arch therefore had been reduced due to the later initiation and there was lesser demand on the gymnast in order to open the hip angle for release in the arch longswing. From a coaching perspective, gymnasts executing the pike longswing may require greater physical preparation and conditioning on the shoulder flexion and hip extension movements to be able to match the target skill and fulfil the demands of this particular longswing technique (Irwin et al., 2005). However, there remains to be no difference between the three longswing techniques when observing shoulder work during the shoulder functional phase. The eccentric action at the shoulder therefore appears more essential to focus on as opposed to the magnitude of work required.

Hip joint work was previously lower in the pike longswing compared to the arch when interpolated to a circle angle of 135° to release. When interpolated to the hip functional phase, the pike longswing was significantly greater than the arch technique in the initial 40% of the first functional phase and remained higher to the conclusion of the longswing. With the pike longswing required to flex at the hips for the first hip functional during the ascent as opposed to the descent in the arch, the pike technique appears to more demanding for the gymnast and require more joint work at the hip. The arch technique appears to be able to control the contribution of the hip joint due to the favourable position caused by the location of the hip functional phase.

The gymnast's energetic interaction with the high bar has been of focal interest in previous literature when investigating the total energy gymnast-high bar system (Kopp and Reid, 1980; Witten et al., 1996; Arampatzis and Brüggemann, 1998; Irwin and Kerwin, 2006; 2007; Kerwin and Irwin, 2010). The earlier work of Okamoto et al. (1987) highlighted the need of muscular work within the backward longswing to overcome the loss in mechanical energy through friction and air resistance. This again highlights the importance of the total

work done by the performer and therefore the energy contribution from the gymnast that within this study, inferred the effectiveness of each longswing technique.

The gymnast energy, together with the bar strain energy and net energy constitute the total energy within the gymnast-high bar system. The total energy profiles within the current study are similar in profile and magnitude to that of Arampatzis and Brüggemann (2001). Energetic values from the current study have been expressed in J/kg in order to allow a comparison with the previous study. The total energy at the start of the longswing and at release were very similar for the three longswing techniques in the current study (8.1 - 8.5 J/kg at the start and 9.4 – 10.0 J/kg at release) and the longswing preceding the Tkachev in Arampatzis and Brüggemann (2001) (8.3 J/kg at the start and 10.7 J/kg at release). Differences between these two studies however are apparent when observing the peak total energy and therefore the decrease in total energy. Arampatzis and Brüggemann (2001) reported a decrease in total energy down to a minimum of 2.0 J/kg before the gymnast reached the bottom of the longswing at 270°, a loss of approximately 6.3 J/kg. In the current study, the arch longswing had an initial loss of 2.8 J/kg, the straddle a loss of 3.3 J/kg and finally the pike with a loss of 4.9 J/kg before they had reached the base of the longswing. These larger differences between the two studies may be due to the difference in bar spacing and therefore the restrictions when passing the lower bar. After the 1996 Olympics the maximum bar spacing was increased from 1.6 m to 1.8 m (FIG, 2013) whereas the data of Arampatzis and Brüggemann (2001) were collected prior to this during the 1994 World Championships. Unfortunately it is unknown which longswing techniques the gymnasts within the study adopted but with possibly greater changes in shoulder and hip kinematics required to pass the low bar successfully, these movement patterns may also remove greater energy from the system (Irwin and Kerwin, 2006).

Differences between the three longswing techniques in the current study have been highlighted in the downswing of the preceding longswings; the pike longswing removed 43% and 34% more energy than the arch and straddle techniques respectively. With a greater deficit in total energy established prior to the ascent phase, the pike longswing would be required to generate more mechanical work in the upswing in order to contribute greater gymnast energy and therefore a similar increase in total energy to its varying counterparts. Total joint work was significantly lower in the pike longswing compared to the arch; however the increase in total energy was the same. A greater bar strain or net energy can therefore be expected in the pike technique.

With the pike longswing illustrating a lesser amount of total work done, it would not be unexpected for this to appear as the less demanding longswing technique of the three variants. However, with a smaller increase in total energy compared to the straddle technique it may be more demanding for the gymnast to successfully perform the straddle Tkachev. Irwin and Kerwin (2006) stated that for a gymnast to complete the general longswing successfully, the difference in total energy between the start and end of the longswing must equate to or be greater than 0. The successful completion of the straddle Tkachev requires this difference to be greater than 0 due to the gymnast requiring movement at release, of which the straddle technique benefits from more. The arch and straddle techniques have therefore gone through a greater physical demand by providing a greater level of mechanical work.

Of the total gymnast energy generated by the arch longswing, only 29% matched that of the increase in total energy in comparison to 43% in the pike technique. With a lower deficit in total energy as the gymnast passes the bar, the arch longswing appears to be successful at controlling the movement patterns throughout the preceding longswing in order to not over expend the gymnast energy. Arampatzis and Brüggemann (2001) reported a similar phenomenon whereby the gymnasts can concentrate on the precision of the movement as opposed to maximising gymnast energy. With elite uneven bar routines emphasising the importance of connecting complex flight skills and combinations of skills, the arch technique may be the more favourable technique in order to have the potential to execute more demanding skills such as the pike or straight Tkachev with the remaining gymnast energy. The addition of a second pull in the horizontal direction on the high bar in the arch longswing may infer that gymnasts are able to utilise the energy return from the high bar as opposed to a greater gymnast energetic contribution.

Determination of whether one longswing technique allowed the gymnast to mechanically work less than another and therefore be less demanding was not possible within the current analyses. The movement patterns that make up the pike technique appear to be more restricting for the gymnast to contribute as much energy and therefore the gymnast may have reached the maximum capacity of gymnast energy that that technique allows the gymnast to contribute. In contrast however, the significantly greater energy loss during the downswing in the pike technique would cause a greater increase in bar strain energy. With the bar being a passive element and only being able to return what energy is supplied to it (Arampatzis and Brüggemann, 1999), the return from the bar during the upswing of the pike technique would be greater and therefore greater gymnast energy would not be

required. Arampatzis and Brüggemann (1998; 1999; 2001) have examined the interaction of the gymnast and high bar closely and the possibility of the gymnast utilising the elastic properties of the bar through muscular work. Arampatzis and Brüggemann (1998) stated that the muscular work performed by the gymnast during the descent phase is essential as it influences the energy transfer between the bar and gymnast. Future research building on from the current study may therefore benefit from investigating the differences in bar strain energy between the three techniques and whether the energy inputted to the high bar varies between techniques.

During the descending phase of the longswing, gymnasts performing the pike technique were most influenced by the position of the low bar and lost the greatest amount of energy compared to the other techniques. However, as previously stated, 70% of work by the gymnast and therefore the gymnast's contribution to the energy system occurs during the ascent phase (Irwin and Kerwin, 2007). Therefore it is ineffective for the pike technique to adopt similar shoulder joint kinetic characteristics of the inward Tkachev reported by Kerwin and Irwin (2010) which has the obstruction of the low bar during this ascent phase. Smaller joint moments and joint powers at the shoulders equate to less shoulder joint work and therefore less energy produced to overcome a deficit in total energy. Consideration must therefore be taken by coaches when considering the components of a gymnast's routine to incorporate combinations of skills to increase complexity. The influence of the low bar on joint kinetics and the energy required for following skills may not permit particular skills and therefore longswing techniques to be performed.

Focusing on the shoulder and hip functional phases, each longswing generated a greater change in total energy due to the start of the functional phase occurring after the gymnast had passed the low bar and therefore close to their minimum total energy. With the pike longswing having the greatest deficit it was the only technique to have a greater change in total energy than gymnast energy. Change in gymnast energy remained lowest in the pike technique due to joint work at the shoulder joint in particular decreasing through the eccentric action prior to release. Examined further, the pike longswing contributed zero gymnast energy in the second shoulder functional phase due to the significant differences in shoulder joint kinetics at release. The significantly greater change in total energy may therefore be attributed to either a greater change in bar energy or net energy. With the pike longswing executing peak vertical bar force prior to the start of the functional phase, it could be assumed that the high bar is recoiling and adding energy back into the gymnast-

high bar system during the first shoulder and hip functional phase. Caution however must be taken in these reported findings due to the characteristics of the bar movements being taken from bar force profiles as opposed to calculated bar energy values. The arch longswing however was yet to reach peak vertical bar force until 40% and 60% through the first shoulder and hip functional phase respectively; attributing to the significantly lower increase in total energy.

The energetic input from the gymnasts through total joint work across the three longswing techniques has been signified through its contribution to the change in total energy of the gymnast-high bar system. Although the pike longswing was executed with less joint work, the energy exchange reported by Arampatzis and Brüggemann (1999) was not as positively influenced. The arch and straddle techniques have gymnast energy in reserve and therefore can focus on executing the skill precisely as well as the potential for more complex versions of the skill being performed; a novel implication of selecting varying longswing techniques. Contrastingly however the arch and straddle technique could be deemed less effective due to not utilising the full gymnast energetic input.

6.5 Conclusion

Chapter 6 aimed to determine whether changes in longswing technique varied the joint kinetics of the preparatory longswing and to examine the energetic demands placed on the gymnast. Longswing techniques are distinguished by the movement patterns at the shoulder and hip joints and although joint kinematics were reported as significantly different, Chapter 4 reported no significant differences in key release parameters. The methods applied in the current study were validated previously in Chapter 5 with the importance of temporal characteristics and overall magnitude emphasised.

The pike longswing executed a significantly earlier concentric action in order to open up the hip joints in the second functional phase. As a consequence the first hip functional phase was significantly shorter and the second functional phase contributed significantly more to the total joint work. The pike technique also performed a significantly greater shoulder flexion moment at release in order to travel backwards over the high bar. The considerably greater eccentric action through negative work however reduced the overall increase in gymnast energy.

The interaction with the high bar varied between the arch and pike longswing where the arch longswing was able to execute a second horizontal pull on the bar prior to release,

allowing for the potential return of bar energy and therefore the significantly earlier release angle. The pike longswing utilised the bar energy return earlier in the longswing with a significantly earlier peak vertical bar force enabling the bar energy return to occur earlier causing an increase in total energy to accommodate the lower change in gymnast energy.

Significant differences in the joint kinetics as the gymnasts passed the low bar caused significant differences in the total energy lost and therefore varying demands on the gymnast during the upswing. Coaches should therefore take into consideration the movement patterns that cause a loss of energy in the initial stages of the longswing and the options for increasing the energetic contribution from the gymnast in the following ascent phase. Technique selection can then be more effective with the knowledge of physical preparation required and the different movement patterns explained.

CHAPTER SEVEN

GENERAL DISCUSSION

7.1 Introduction

Artistic gymnastics is a sport that exemplifies physical strength, technical finesse with a high level of accuracy and precision. Women's Artistic Gymnastics in particular relies heavily on the mind-set of the coach (Irwin et al., 2005) where their coaching background and philosophy can determine the technique selection process. Coaches observe skills as a series of body shape changes and movement patterns which raises the issue that without mechanical understanding, techniques for the same skill that appear similar do not have an effective selection criteria applied. Changes in body shape could cause biomechanical changes that are unobservable to the coach's eye. Mechanical knowledge and understanding of varying techniques could therefore provide coaches with an established technique selection criterion resulting in educated guess work and trial and error methods being reduced and coaching becoming more effective and efficient (Cross and Lyle, 2002; Irwin et al., 2005; Sands et al., 2011).

Within artistic gymnastics, on each apparatus there are key skills, which directly link to the development of other more complex skills (Irwin and Kerwin, 2006; Hiley and Yeadon, 2007; Sands et al., 2011). On the uneven bars one of these key skills is the longswing which is directly associated to the development of more advanced skills. The inclusion of more complex skills is essential to keep up with the ever evolving sport and the advances in difficulty and diversity (FIG, 2013). A review of research undertaken in Chapter 2 identified that varying techniques in performing the same skill has not been addressed previously, even though the selected skills have had a vast amount of research focus. Key determinants to the success of the longswing have been reported in the shoulder and hip characteristics (Cheetham, 1984; Prassas et al., 1998; Arampatzis and Brüggemann, 1999; Yeadon and Hiley, 2000; Hiley and Yeadon, 2003; 2005; Irwin and Kerwin, 2006). Therefore, if there are varying movement patterns observed, the resulting mechanical consequences need to be investigated. Research in Men's Artistic Gymnastics has dominated the focus of much research providing insight into the skill of the longswing. However, with the added influence of the low bar in the female longswing, previous research may not be readily applicable forming a gap in Women's Artistic Gymnastics research. Therefore a distinct mechanical insight into the development of the female

longswing was warranted and was the focal point of the thesis. The research presented in the current thesis has been focused on using scientific methods to understand and explain technique selection with the overall aim of increasing knowledge and understanding of the biomechanics underpinning varying techniques of the female longswing for the determination of effective technique selection. Through a thematic approach identified in Chapter 1, the overall aim was addressed through five separate themes; contemporary trend analysis, biomechanical conceptual approach, validation of methods, biomechanical musculoskeletal approach and biomechanical energetic approach. Within Women's Artistic Gymnastics there is currently no technique selection criterion to provide an effective selection procedure; increased biomechanical knowledge and understanding addressed that.

Theme 1: Contemporary Trend Analysis: An initial trend analysis taken part at the two International competitions provided the research with high ecological validity and elite meaningful groundings. By identifying the frequency and nature of skills being performed within this environment, scientists and coaches maintain high levels of confidence in the findings and implications. As a result of the trend analysis of skills and techniques, it was identified that the longswing preceding the straddle Tkachev would be the focus of this research due to it being the most frequently performed release and re-grasp skill. Three distinct longswing techniques were identified and although the longswing is classified the same as one another (FIG, 2013) it becomes important to know which technique is most effective and why. This knowledge provided novel information to coaches within the training environment where coaches and gymnasts are searching for effective and efficient training strategies. Underpinning the technique selection process is the observation of movement patterns by the coach that distinguishes differences in technique, supporting much of the coach education across the globe (British Gymnastics, 2007; FIG, 2013). However, what is absent from technique selection is knowledge of a scientific criteria based on the biomechanics underlying the success of these distinct techniques. As such a conceptual understanding of technique selection is required (Irwin et al., 2005) which would quantify movement patterns (joint angular kinematics) and performance variables that coaches could use to differentiate between techniques (angular momentum), which were addressed in Theme 2.

Theme 2: Biomechanical Conceptual Approach: Kinematic analyses within this theme provided a description of the movement and assisted in formulating the coaches understanding of the differences in techniques during key phases of the skill i.e. .functional

phases and release (Kerwin and Irwin, 2010; Manning et al., 2011). In addition an angular momentum analysis provided further biomechanical conceptual understanding of the differences between these techniques globally (angular momentum around the mass centre and bar) and locally (angular momentum of the segments). Knowledge of how the angular momentum characteristics and release parameters vary as a function of technique provides coaches with greater mechanical understanding to differentiate technique and assist in their selection process. These measures are not easily or immediately accessible to the coaches and demonstrate how biomechanics and coaching can interface to increase knowledge.

In order to build from Theme 2 and examine the physical demands of each technique in the elite competition environment (Theme 4: musculoskeletal and Theme 5: biomechanical energetic processes), methodological issues surrounding the errors associated with the field based analyses needed to be resolved; as such a sensitivity and validation investigation was undertaken through Theme 3.

Theme 3: Method Validation: Building on the issues associated with the indirect measurement of joint kinetics (Hatze, 2000; 2002; Robertson et al., 2014) and the work of Challis and Kerwin (1996) a sensitivity analysis provided an investigation into the errors associated with inverse dynamics calculated in the field. Data collected in the field were also validated against pseudo criterion data collected in a controlled environment employing direct methods in order to investigate the influence on joint kinetics. With the indirect methods of inverse dynamics validated and a measure of the errors associated known, the final themes were examined.

Theme 4: Biomechanical Musculoskeletal Approach: Joint kinetics provided a measure of the differences in physical demand placed on the gymnasts performing varying techniques. Establishing whether one technique required different joint kinetic inputs from the gymnast than another would allow the coach to understand the musculoskeletal demand being placed on the performer and have implications for both physical preparation and potentially injury. The subsequent theme adapted the approaches used by Arampatzis and Brüggemann (1999, 2001) and Irwin and Kerwin (2007) to examine the energetic contribution of the gymnast and further extended the research of these papers.

Theme 5: Biomechanical Energetic Approach: This theme provided a holistic approach that gave an estimation of the overall energy cost of these techniques and the contribution of the gymnast's physical input into the total gymnast bar energy system. The implications of these findings rest with increasing knowledge and understanding of the interaction of the gymnast with the system which has the potential to allow coaches to tailor the

gymnast's physical preparation, technique development to these demands (Irwin and Kerwin, 2007; Irwin et al., in press) or even which technique is selected.

Each theme is addressed via a series of research aims that will be considered in the subsequent sections of this discussion (7.2). This is followed by a discussion of the contributions to knowledge (7.3), which included thematic biomechanical framework, implications for coaching and research philosophy. Recommendations for future research and limitations are examined (7.4) and a final note with concluding remarks completes the discussion (7.5).

7.2 Addressing the Research Themes

Artistic gymnastics is governed by the Code of points set out by the International Federation of Gymnastics (FIG) and dictates the essential requirements of an uneven bars routine (FIG, 2013). With the distinction of difficulty and complexity within the scoring system, flexibility is given to the gymnasts and their coaches in the skills forming their competitive routine. Therefore, Theme 1: Contemporary Trend Analysis (Chapter 3) was essential in the determination of what skills elite gymnasts were performing and what longswing techniques they were employing preceding complex release and re-grasp skills. As such the aims of Chapter 3 were to identify and develop knowledge of varying longswing techniques and the proceeding skill and secondly to increase understanding of the influencing factors (stature, mass and nationality) on technique selection. The main observations were that 55% of gymnasts performed the straddle Tkachev and executed three distinct longswing techniques; arch, straddle and pike. From a visual perspective the hip joint plays a dominant role in the differentiation of longswing technique due to its larger range of motion visible to the coach's eye. A traditional coaching view point is that the longswing technique selected is based on the gymnast's stature (Still, 1990); shorter gymnasts adopt the arch longswing technique and taller gymnasts the pike. Chapter 3 identified that there appeared to be a trend between the longswing technique selected and gymnast stature and nationality. Due to the biomechanical nature of this thesis nationality was not investigated any further, but it's relevance within the coaching discipline is recognised. Gymnast stature and longswing technique formed the foci of the subsequent themes application to addressing the overall thesis aim. In order to develop an accurate, scientifically grounded conceptual understanding of the differentiation of the varying longswing techniques and work towards the overall aim of determining the most effective longswing technique, a biomechanical approach was taken. The implication would be that

coaches can further identify the differences in technique and gain knowledge on the influences of joint angular kinematics and key performance variables (angular momentum) on key phases and release parameters.

As identified in Chapter 3 and supported by Hiley and Yeadon (2003), varying longswing techniques consist of varying temporal and spatial characteristics at the shoulder and hip joints. The successful execution of the longswing and following skills has been attributed to the shoulder and hip joints (Witten et al., 1996; Arampatzis and Brüggemann, 1998; 1999; 2001; Hiley and Yeadon, 2003; Irwin and Kerwin, 2005; 2007; Kerwin and Irwin, 2010) and the defined functional phase (Irwin and Kerwin, 2005). During the backward longswing, hyper-flexion to extension at the shoulders and hyper-extension to flexion at the hips have been two functional phases of paramount importance. Theme 2: Biomechanical Conceptual Approach (Chapter 4) aimed to investigate the underlying mechanics of three distinct longswing techniques with the principal aim of identifying any differences in functional phase characteristics and whether a particular longswing technique generated superior release parameters.

Eighteen successful straddle Tkachevs were selected from elite International competitions and grouped according to the longswing technique performed (arch, straddle and pike) to establish any differences in the underlying mechanics. Of the random sample selected there were no significant differences between longswing technique and gymnast height or total limb length. A large effect size was established between an increased stature and the performance of the arch and pike techniques suggesting its influence on technique selection. Through the application of biomechanics and building on from the functional phase definitions of Irwin and Kerwin (2005) and the observation of two hip extension and one flexion phase by Arampatzis and Brüggemann (2001), Theme 2 (Chapter 4) identified significant differences between the longswing techniques and the two functional phase locations at the shoulders and hips. The arch longswing initiated the shoulder and hip functional phases significantly earlier than the straddle and pike techniques with greater hip hyper-extension. Previous research has reported that earlier hip extension can increase angular momentum at release (Hiley and Yeadon, 2005) providing the gymnast with optimal release conditions in order to effectively perform the Tkachev. Gymnasts performing the arch longswing completed the first hip functional phase over a significantly larger circle angle than the pike technique, allowing a greater amount of time in the fully extended position known to promote the energetic processes required for the successful completion of the longswing (Witten et al., 1996; Arampatzis and Brüggemann, 1999).

Although previously not termed functional, the phase of hyper-extension to flexion at the shoulders and hyper-flexion to extension at the hips is paramount in preparing the gymnast for release and as such was termed the second functional phase. The straddle technique in particular executed a significantly later second hip functional phase resulting in the gymnast remaining in contact with the bar for the longest.

When focusing on differences in release parameters between the three longswing techniques, gymnasts executing the arch longswing released significantly earlier than the straddle and pike techniques implying a longer flight time in the arch technique but less flight height. This finding concurs with Kerwin and Irwin (2010) who reported similar differences in release angle between different versions of the Tkachev. With the release angle information, coaches may be able to effectively select the technique that generates the particular flight path they may desire in order to either provide the gymnast with more time to complete the skill or potential to perform more complex versions. The remaining release parameters were the same across all three longswing techniques except with high effect sizes in greater horizontal velocity and angular momentum for the arch longswing compared to the pike. From a coaching perspective, these findings suggest the arch technique would increase the possibility of performing a combination of skills (linking Tkachevs), a key component in the process of increasing the complexity of the routine in the coordinated direction (Arkaev and Suchilin, 2004; Irwin et al., in press). For example, a straddle Tkachev followed by another release and re-grasp skill would increase a gymnast's difficulty score by adding a connection value of 0.2 (FIG, 2013).

Gymnasts executing the three longswing techniques were equally effective in completing the straddle Tkachev successfully with limited differences in release parameters. To assist in technique selection of the skill, the physical demands of each technique required further investigation in an attempt to explain the kinematic differences observed. As such the indirect method of inverse dynamic analysis (IDA) was warranted as the methodological approach with the added rationale of increased difficulty in non-invasively obtaining kinetic data from elite competition data. With the aim of maintaining high ecological validity in order to provide coaches with meaningful and representative data, method validation (Theme 3) was carried out.

When collecting kinetic data in the field, the researcher is faced with limitations in terms of competition structure, equipment design, facility layout and the fact that motion analysis markers are prohibited during competition. Direct methods of force measurement previously utilised by researchers in the collection of kinetic data are therefore not

applicable to the current study (Kopp and Reid, 1980; Ishi and Komatsu, 1987; Arampatzis and Brüggemann, 1998; 1999; 2001; Hiley et al., 1999). The indirect method of IDA to calculate joint kinetics has well reported issues (Robertson et al., 2014; Hatze, 2000; 2002) and the confidence in this iterative process was highlighted by the salient work of Challis and Kerwin (1996). As such the application of Theme 3: Validation of Methods (Chapter 5) aimed to firstly investigate the errors associated with IDA and secondly validate the use of field based measures in the calculation of joint kinetics in longswing technique. Sensitivity analyses were performed by manipulating key inputs to the IDA calculation. The main findings highlighted that the key influences in the errors associated with IDA were cut off frequency and joint centre location. The cut off frequency did not significantly influence the joint centre locations however did result in significant changes in the joint kinetic outputs. This finding highlighted the importance of appropriate noise removal techniques and the need to consider the specific nature of the data. Errors around 10% are not uncommon for 3D video data and results reported in Chapter 5 compare favourably to previously conducted sensitivity analyses (Irwin, 2005).   The second objective of Theme 3 (Chapter 5) was to examine the influence of competition based data collections on the calculation of joint kinetics using the IDA method.

Through the reconstruction of a pseudo competition arena within a controlled environment, indirect and direct methods of data collection were analysed to examine differences in joint kinetics.   Consistent differences between the two methods employed were reported highlighting the systematic error associated with these two modes of data collection. Joint moment data in the pseudo competition and lab conditions compared favourably to previous research utilising these same methods (Arampatzis and Brüggemann, 2001; Kerwin and Irwin, 2010; Irwin et al., in press). Joint power and joint work results were largely affected by digitising accuracy that predominantly overestimated peak values. Confidence can be sustained in the temporal characteristics and overall magnitude of the joint kinetic data, but caution should be taken in reporting peak joint kinetic values in the preparatory longswing preceding the straddle Tkachev.

Confidence was established in the estimation of internal joint kinetics, firstly in terms of the sensitivity of the inputs into the IDA process and secondly in terms of the pseudo competition data collections. With this new knowledge of the errors associated with IDA applied to the female longswing, this research was able to examine the demand of each varying longswing technique. Theme 3 therefore provided validation for the subsequent

chapter that would assist in addressing the aim of determining the most effective technique for a given skill.

Joint kinetic analyses provide coaches with knowledge and understanding of the physical demand of each longswing technique. The underpinnings of the principal movement patterns identified previously have impacts on the physical preparation required by the gymnast and the potential development of the straddle Tkachev; for example development to perform the straight Tkachev. Theme 4**:** Biomechanical Musculoskeletal Approach (Chapter 6) examined the joint kinetics and provided a quantification of the musculoskeletal demand on the performer. This was addressed in the first aim of Chapter 6 which investigated the underlying joint kinetics of the varying longswing techniques to explain the physical demand on the gymnast.

Using the validated IDA methods from Chapter 5 the key findings included the pike longswing demonstrating significant differences in joint kinetics compared to the arch and straddle techniques. The significantly earlier onset of the concentric hip action to open up the hip joints in the second hip functional phase resulted in the first functional phase to be significantly shorter. The pike longswing's second functional phase was also greater in joint work contribution whereas there was no clear dominant phase in the comparative techniques. From a coaching perspective, when selecting the pike technique, coaches have the knowledge to administer conditioning and physical preparation that focuses on hip extension to justify this technique as an effective one. Similarly at the shoulder joint, the pike longswing generated a significantly greater shoulder flexion moment in order to prepare the gymnast for release. Conditioning exercises that mimic or consider this shoulder action would therefore be beneficial for gymnasts adopting the pike technique to execute the straddle Tkachev successfully and effectively. Replication of key phases of the target skill in progressions to develop gymnastic movements was examined previously (Irwin and Kerwin, 2007). The current research provides coaches and scientists with a greater understanding of the role of joint kinetics in the successful execution of the Tkachev, which will facilitate the development of progressions or training drills.

Theoretically building on from joint kinetics to incorporate an energetics analysis provides insights into the interaction of the gymnast with the total gymnast bar energy system. This approach has implications in terms of understanding the technical and physical demand on the gymnast. As such Theme 5: Biomechanical Energetic Approach (Chapter 6) built on from joint kinetics to a more holistic approach to examine the biomechanics energetic processes. This was addressed in the second aim of Chapter 6 which was to examine and

explain the energetic processes employed by the gymnast to contribute to the gymnast-high bar energy system. The key findings highlighted that as the gymnast passed the low bar during the pike longswing, the movement patterns caused a significant loss in total energy that needed to be compensated by the gymnast energy contribution during the upswing. With 100% of the gymnast energy required to overcome the deficit in total energy, the energy return from the bar from the earlier transfer in the descent phase may play a paramount role in the effectiveness of the pike longswing technique. The significantly earlier peak vertical bar force in the pike longswing (Figure 6.3b) would suggest an earlier return of bar energy as the gymnast passed under the bar, which is not characteristic of the arch and straddle technique but results in a similar increase in total energy. The increase in total energy observed in the arch and straddle technique was due to the increase in gymnast energy input. However, during the pike longswing at release, the hyper flexion at the shoulder joints resulted in a lower gymnast energy contribution. Gymnasts executing the arch longswing interacted with the bar in such a way that a second peak in horizontal bar force occurred at release. With the link between bar force and bar energy, it is reasonable to suggest that the significantly different horizontal bar force may explain the double dip in total energy as energy was transferred into the bar. Therefore, compared to the pike, a significantly earlier release angle and the greater horizontal velocity at release were observed in the arch technique. The gymnast during the arch longswing seems to be able to effectively control the movement patterns up to release by utilising additional energy returned from the bar. As a consequence, the gymnast energy contribution maybe reduced during the arch longswing and this extra capacity can be used to develop more complex uneven bar skills or combinations of skills.

7.3 Contributions to Knowledge

7.3.1 Thematic Biomechanical Framework

In order to address the overall aim of this thesis, increase knowledge and understanding of the biomechanics underpinning varying techniques of the female longswing for the determination of effective technique selection, five themes were explored (contemporary trend analysis, biomechanical conceptual approach, validation of methods, biomechanical musculoskeletal approach and biomechanical energetic approach). These identified, described and explained the biomechanics of the female longswing and technique selection. The initial trend analysis (Theme 1) at the forefront of the thesis has provided coaches and researchers with data that described and quantified the frequency and nature

of skills being performed at International competition. Very few studies have acknowledged the vast number of skills performed by world leading gymnasts at that particular moment in time at elite level competitions. This thesis has also identified that there are certain skills performed in a variety of ways to produce the same outcome. Building on from previous research this thesis contributed new knowledge and understanding of different techniques to perform the same skill as opposed to different skills performed as investigated by (Brüggemann et al., 1994; Arampatzis and Brüggemann, 1999; Kerwin and Irwin, 2010). With the FIG classifying these skills the same, this research has provided coaches with an insight into why certain techniques may be more effective than another based on the demands of the gymnast or following skill itself. This approach adds to the richness and ecological validity of the research, specifically adding meaningfulness to the overall direction of the thesis.

Central to a coach's knowledge of technique is the formation of a conceptual mind-set of how a skill works. Visual observation of movement patterns and key characteristics of skills are used to facilitate this understanding. Building on the research of Irwin et al. (2004; 2005), a joint angular kinematic analysis described the three longswing techniques during the keys phases of the skill and examined the important variable of angular momentum in Theme 2: Biomechanical Conceptual Approach. One key contribution to knowledge that emerged from Theme 2 was the identification of a second functional phase. The functional phases have previously been defined as hyper-flexion to extension at the shoulders and hyper-extension to flexion at the hips (Irwin and Kerwin, 2005). This thesis has provided novel insight into the existing functional phase theory by identifying and quantifying that two functional phases exist in the three varying techniques for the preceding longswing prior to the straddle Tkachev. The angular position of the gymnast within the circle angle as well as the magnitude and distribution of joint kinematics were reported for the varying longswing techniques. By establishing the second functional phase at the shoulder and hip joints, the requirement of varying physical preparation due to differences in technique could be focused within the defined functional phases.

In order to establish underlying explanations of the differences in kinematics and explore the musculoskeletal demand on the gymnast, a process of validating methods (Theme 3) was undertaken. A novel approach was used which replicated a competition environment within a controlled laboratory setting which bestowed a comparison of field and lab data inputs. This approach provided confidence in the subsequent joint kinetics and energetics analyses. This research has built on from and adapted previous sensitivity analyses by

applying the examination to a more dynamic movement and by comparing the calculation of inputs to IDA with their direct counterparts. Within the field of artistic gymnastics, sensitivity analysis has been employed to the estimation of bar forces (Kerwin and Irwin, 2006) but has not to the best of the author's knowledge been applied to joint kinetics and the subsequent mechanical findings. Theme 3 provided two new contributions to knowledge; firstly, it identified the level of random error associated to the calculation of joint kinetics in a novel gymnastic skill, building on from the simple lab movements of Challis and Kerwin (1996). Secondly, the systematic error identified between lab and field based data collections gave confidence in the validity of this approach and useful information for future studies of this nature.

The final technique analyses were incorporated into Theme 4 (biomechanical musculoskeletal approach) and 5 (biomechanical energetic approach). The joint kinetic analysis provided two contributions to knowledge; in the first instance providing coaches and scientists with original information that is unobservable by eye in the identification of varying movement patterns and secondly, a more detailed picture of the physical demand that these skills require to be perform successfully. For example, this research clearly identified that one particular longswing technique (the pike longswing) would benefit from different physical preparation exercises due to the specific hip and shoulder joint kinetics. In addition the dominant contribution of the hips during the second functional phase was highlighted.

The final theme (biomechanical energetic approach) provided a holistic approach to understanding and explaining the gymnast-bar energetic system. This approach focused on the gymnast's energy input into the system during the three-longswing techniques. Building on the concepts addressed by Arampatzis and Brüggemann (1999; 2001) and Irwin and Kerwin (2007), the major contribution to knowledge was highlighted as identifying the arch longswing as a technique that may provide the gymnast with the potential to utilise the energy capacity that may exist and perform more complex versions of the Tkachev or skill combinations.

The thematic biomechanical framework has brought together a mixed methods approach that has added to the body of knowledge and understanding of mechanics underlying these skills. The trend analysis provided the platform for a meaningful research direction and in combination with complex biomechanical analysis has addressed the thesis aim and demonstrated that there is a link between grounded scientific methods and technique selection.

7.3.2 Implications for Coaching

The gymnastics coaching community are aware of the varying longswing techniques that exist, however, the potential benefits of the differing versions remains unexplained. The thesis provides scientifically grounded in-depth knowledge of these differences, in an ecologically valid environment. This new knowledge advances the conceptual understanding of the movement patterns and musculoskeletal demand placed on the gymnast during each version of the longswing.

From the training principles of specificity and overload, the development and ultimate performance of the varying longswing techniques required that the conditioning and physical preparation exercises closely match the varying demands of the techniques (kinematically and kinetically). As such the rapid eccentric action at the shoulders during the performance of the pike longswing would require conditioning to replicate these actions that the comparative longswing techniques would not necessarily benefit from.

The implications for coach education are apparent and the findings of this thesis can assist in coaching workshops nationally and internationally by informing coaches of the implications of the technique selection process. For example, traditional coaching views may focus on movement patterns that the coach can see (Sands et al., 2011) and therefore select the pike longswing because they have observed this technique shortens the gymnast length during the descending phase and enables them to pass the low bar clearly. New knowledge presented in this thesis into the joint kinetics and energetic demands of varying longswing techniques provides the coach with an understanding that the pike technique removes more energy from the gymnast-bar energetic system and requires the gymnast to work harder on the ascending phase.

Knowledge of the alternative techniques i.e. the arch, means the coach can make an informed decision about the evolution of more complex versions of this skill. Specifically it might be advantageous to perform the arch longswing due to the fact the requirement of gymnasts energy is lower, and that if utilised could place the gymnast in a favourable position to perform more demanding versions of the Tkachev.

7.3.3 Research Philosophy

The research philosophy of this thesis was based on the use of scientifically grounded theories of human movement biomechanics in combination with the theories of the coaching processes to address a meaningful research area that has generated new scientific knowledge and practical implications to the coaching community. Exploring five key

research themes supported this research philosophy (contemporary trend analysis, biomechanical conceptual approach, validation of methods, biomechanical musculoskeletal approach and biomechanical energetic approach). Through the application of trend, technique and methodological analyses, the differences in technique of a particular skill were identified and explained. Developing new insights into detailed biomechanics (kinematics, kinetics and energetics) underlying the successful performance of these techniques highlighted the potential benefits of each version. Integrating coaching knowledge into these findings allowed recommendations in terms of appropriate physical preparation and technique selections that aim to make performance more effective.

Meaningfulness of research was at the forefront of this research philosophy and was achieved by ensuring ecological validity permeated the research themes. Data collected at two of the most prestigious International competitions provided comprehensive evidence of the variations of longswing techniques performed within an ecologically valid environment of the highest possible standard. Gymnasts competing at the Olympic Games and World Championships train to their physiological limits and can be guaranteed to be performing at their maximum. Theme 3 evaluated the issues associated with high levels of ecological validity with the reconstruction of a pseudo competition within a controlled environment to demonstrate the errors present. A challenge to the applied scientist is finding the balance between meaningfulness of real world data and scientific rigor; which I believe this research philosophy achieved.

7.4 Limitations and Future Investigations

7.4.1 Limitations

Undertaking applied research, particularly in a sporting environment with elite performers, is often challenging and can lead to some limitations in terms of data accuracy and reliability that one would achieve in laboratory conditions. Analysing elite athletes at the height of their performance within a competition environment provided this thesis with data that was meaningful and scientifically rigorous; however there were a number of limitations to this approach.

The researcher was limited to the competition schedule and therefore restricted to one trial for each of the selected gymnasts. Small sample sizes are a common feature when undertaking research at elite competition in order to gain high levels of ecological validity (Elliott et al., 2006). The likelihood of type II errors were potentially increased due to the

purposeful sampling that may have adversely affected the identification of differences (Mullineaux et al., 2001). In order to overcome this, effect sizes were included to provide a measure of the meaningfulness of differences.

Collecting image data at 50 Hz could be seen as a limitation to the subsequent analysis due to the systematic differences established in Chapter 5 between 3D video data and Coda Motion analysis data. However, increasing the sampling frequency to match that of the automated motion analysis system, 200 Hz, would not be practical due to the large volumes of data and the limitations of continuous recording at such a high sampling rate. In addition, 50 Hz is the most common sampling rate used in studies of this nature. As technology progresses one would hope that higher sample rates would be possible, however for many gymnastics skills which are of a low frequency, high speed cameras would not be necessary.

7.4.2 Future Investigations

Looking to the future it is apparent that a number of relevant research questions have emerged that would further the understanding of the techniques selection process. Specifically, the future direction of this research can be considered to exist from two perspectives; firstly methodology and secondly data analyses. Methodologically, IDA may have been enhanced through the incorporation of bar torque. In the current research literature this measure is yet to be incorporated into a joint kinetic analysis. One main factor restricting its use is the fact that the calibration of bar torque is particularly challenging to the scientific community. Secondly, from a data analysis perspective, bar strain energy could be incorporated to allow the gymnast-high bar interaction to be further examined. However, in the current studies this was not possible due to the indirect bar force measured and errors that would have been associated with bar stain calculations. Within the field environment direct bar measures are rare to occur due to their obtrusive nature.

The current study found there was no significant difference in gymnast morphology and longswing technique selected, however there was a large effect size and it remains a strong traditional coaching view. Developing a more holistic approach and combining biomechanics with coaching theory, further investigations into the aetiology of technique selection and the coaching processes would further understanding in this area.

The overall aim of this research was to increase knowledge and understanding of the biomechanics underpinning varying techniques of the female longswing for the

determination of effective technique selection. This aim has been addressed and in the future this research could be built on to develop methods that would allow performers to optimise their technique selection for their specific physical, psychological and motor control requirements. This thesis provides the first step in a research approach through innovative analyses that provides original understanding of the mechanisms underpinning varying techniques that could individualise measures to select the best techniques for specific gymnasts. With the safety of the gymnast central to this research it would be aimed at making training more effective and efficient.

7.5 Final Note

The aim of this thesis was to increase knowledge and understanding of the biomechanics underpinning varying techniques of the female longswing for the determination of effective technique selection within uneven bar performances in Women's Artistic Gymnastics. By addressing this research aim, the arch and straddle longswing were established as the key techniques for the effective development of more complex skills with the pike longswing requiring more specific physical preparation.

An initial contemporary trend analysis (Theme 1) concluded that the straddle Tkachev is a key skill in the development of high scoring, complex routines and is the most frequently performed release and re-grasp skill by elite female gymnasts. Three distinct longswing techniques were reported to precede the straddle Tkachev where a subsequent biomechanical conceptual approach (Theme 2) determined the technical requirement of these varying longswing techniques. A detailed examination of the underlying musculoskeletal (Theme 4) and biomechanical energetic (Theme 5) processes followed on from a validation of methods (Theme 3), which determined the effectiveness of each longswing technique to inform the technique selection process.

This research has provided coaches and scientists with further insights into the trends in elite gymnastics competition and identified varying longswing techniques to perform the Tkachev. Initial biomechanical analysis has provided knowledge of the techniques performed and will help develop coach's conceptual understanding of these skills. Further new knowledge is provided from the more in depth approaches of joint kinetics and biomechanical energetics providing coaches and scientists with insights into the underlying mechanisms controlling these skills.

The biomechanical energetic analyses highlighted potential development opportunities one longswing technique can provide by having the capacity to increase the performance of the straddle Tkachev and potentially lead to the development of more complex versions (e.g. straight and combinations). Coaches now have access to knowledge they can employ to select specific physical preparation activities based on the biomechanics of the specific longswing technique and scientists have the opportunity to develop this research area with the aim to optimise the technique selection process.

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APPENDIX I

2000 OLYMPIC GAMES AND 2007 WORLD CHAMPIONSHIPS GYMNAST PROFILES

Table AI.1. Gymnast profiles showing physical characteristics, competition, longswing technique selected and their individual rankings from the qualification round

Gymnast #	Height (m)	Mass (kg)	Age (yr)	Competition	Longswing	Ranking
1	1.55	43.0	16	2000	Arch	15
2	1.42	44.0	16	2000	Arch	7
3	1.40	30.9	16	2007	Arch	41
4	1.40	34.0	14	2007	Arch	1
5	1.54	44.0	14	2007	Arch	13
6	1.50	38.0	16	2007	Arch	45
Average	1.47	39.0	15			20
	(± 0.07)	(± 5.6)	(± 1)			(± 18)
7	1.47	35.0	15	2000	Straddle	4
8	1.52	47.6	21	2000	Straddle	21
9	1.55	44.9	22	2000	Straddle	69
10	1.40	32.0	15	2007	Straddle	16
11	1.50	36.8	17	2007	Straddle	2
12	1.47	46.0	17	2007	Straddle	77
Average	1.49	40.4	18			32
	(± 0.05)	(± 6.6)	(± 3)			(± 33)
13	1.65	52.6	18	2000	Pike	50
14	1.51	46.0	16	2000	Pike	18
15	1.49	44.0	17	2000	Pike	21
16	1.60	46.7	19	2007	Pike	60
17	1.58	44.0	21	2007	Pike	36
18	1.50	41.0	17	2007	Pike	5
Average	1.55	45.7	18			32
	(± 0.06)	(± 3.9)	(± 2)			(± 21)

APPENDIX II
WINTER'S RESIDUAL ANALYSIS

For a selected longswing preceding the straddle Tkachev from the Sydney 2000 Olympic Games, vertical and horizontal coordinates of seven digitised points (fifth metatarsophalangeal, lateral malleolus, femoral condyle, greater trochanter, estimated centre of rotation of the glenohumeral joint, lateral epicondyle of the elbow and wrist) were subject to a residual analysis (Winter, 2009). Each data set was filtered using a low pass digital filter at cut off frequencies ranging 1-20 Hz in 1 Hz increments. Residuals were calculated by the RMSD between unfiltered and filtered data at the selected cut off frequencies and plotted against cut off frequency (Figure AII.1)
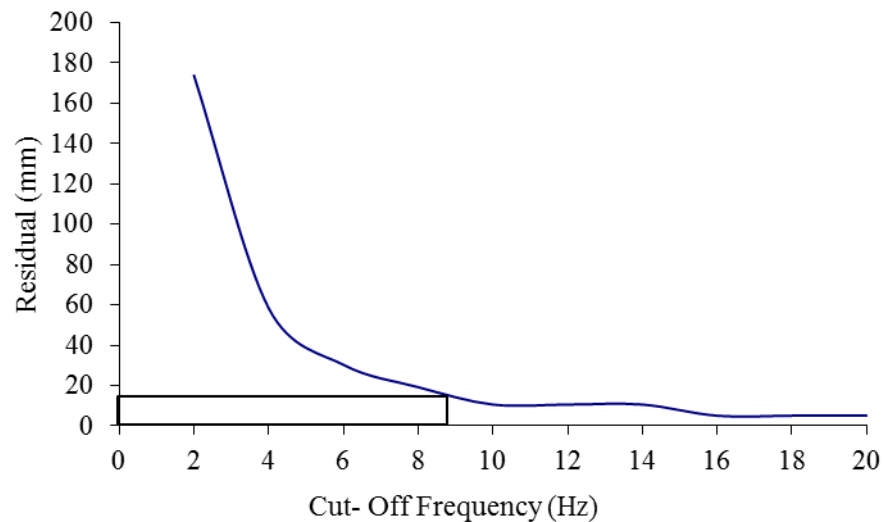

Figure AII.1. Example of residual analysis (Winter, 2009) performed on the vertical coordinate of the left greater trochanter.

Winter (2009) reported that an equal balance between signal distortion and the amount of noise allowed through the filter was the optimum approach. With an estimation of the noise residual represented by the y-intersect, a straight line intersecting the residual line determined the optimal cut of frequency. Due to the frequency differences between markers, each joint centre specified above was included in an individual residual analysis with the cut off frequency then averaged to apply to the full data set. The optimal cut off frequency was calculated at 8 Hz.

APPENDIX III

DETERMINATION OF LAB-BASED BODY SEGMENT INERTIA PARAMETERS

Gittoes et al. (2009) conducted an image based procedure in order to collect anthropometric measurements for the determination of body segment inertia parameters. The above authors reported this method as a practical comprise for athletes within a laboratory environment compared to the timely nature of collecting direct measurements (Yeadon, 1990). Gittoes et al. (2009) reported an accuracy of 2.87% to the subjects directly measured body mass which compared favourably to using direct measurements (2.10%). With Kerwin et al. (1990) similarly calculating segment inertia parameters from front and side images of seven male gymnasts prior to the 1988 Seoul Olympic Games where anthropometric data was obtained, the method of Gittoes et al. (2009) was deemed appropriate as a lab based measure with the method reported below.

Participants were asked to stand in a stationary position within a calibrated volume as illustrated in Figure A.III.1 below. A Canon EOS 400D digital camera (Tokyo, Japan) was used to capture images of the participant in a frontal and left and right sagittal position, with the required body landmarks within the calibration plane.
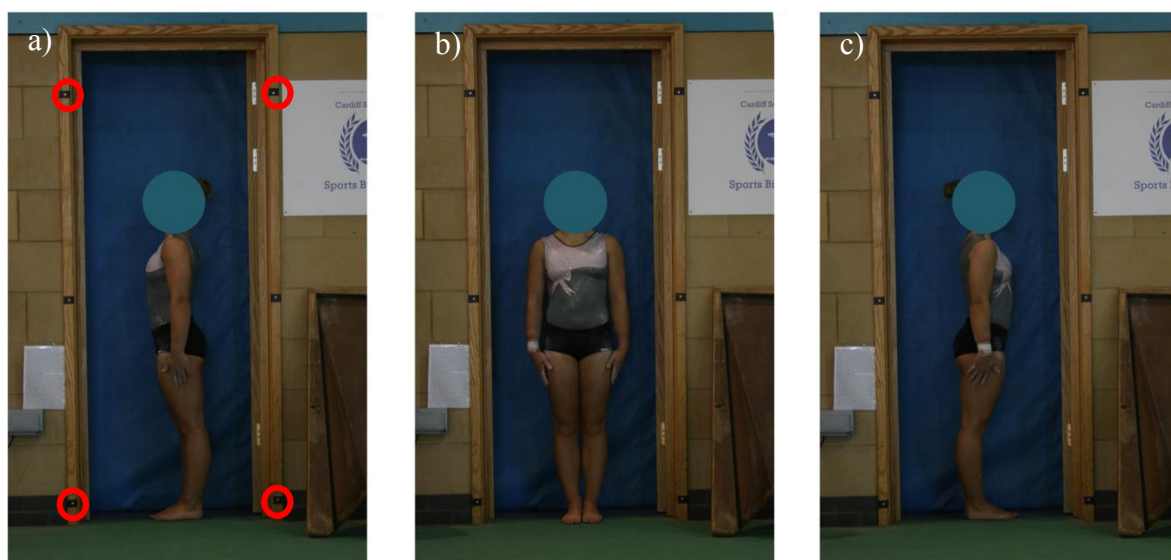

Figure A.III.1. Whole body images and calibration points (**O**) of the a) frontal plane, b) left and c) right sagittal plane view.

Each digital image was digitised using PEAK Motus software (Vicon Peak 9.0, UK) for 10 frames including the four known calibration points (Figure A.III.1) and the 45 defined body landmarks as identified by Yeadon (1990). Coordinates were reconstructed within

PEAK Motus software corresponding to the requirements of Yeadon's (1990) inertia model. Segment lengths and widths were defined from the frontal plane image, segment depths from the sagittal plane images and segment perimeters were derived from segment depths and widths. Measurements determined from the image data were combined with Dempter's (1995) density values and inputted to Yeadon's (1990) inertia model to provide the lab based, customised body segment inertia parameters.

APPENDIX IV

THE INFLUENCE OF THE INERTIA SCALE FACTOR ON JOINT KINETICS

Introduction: A four segment model consisting of the gymnasts arms (hands, forearms and upper arms), trunk (including head and neck), thighs and shanks (including feet) was used to represent the female gymnasts executing the preparatory longswing by averaging the raw coordinate data for the left and right side of the body. Irwin and Kerwin (2001) reported the sufficient use of 2D processes in the analysis of the longswing together with the assumption of bilateral symmetry. With the added influence of the position of the low bar, an additional technique was utilised by female gymnasts is the straddle longswing. To take into account the out of plane movement, an inertia scale correction factor was included within the customised Mathcad programme (Kerwin, 2013) where the inertia values of the lower limbs (thigh and shank) were scaled to the new average length. The aim of this sensitivity analysis was to determine the influence of the inertia scale factor on joint kinetic and energetic outputs

Method: One International female gymnast (age 15.9 years, height 155 cm, mass 59.6 kg) performed three straddle Tkachevs and three general longswings executing the straddle longswing technique. Joint kinetic (JM, JP, JW) variables at the shoulders, hips and knees and segmental energetics (E_{Arm}, E_{Trunk}, E_{Thigh}, E_{Shank}) were then compared with and without the inertia scale factor applied. Data without the inertia scale factor encompassed inertia data for the thigh and shank scaled to the average limb length of the gymnast as opposed to the virtual four segment model limb length. Root Mean Square Difference (RMSD) and percentage Root Mean Square Difference (%RMSD) were then calculated with each RMSD being divided by the range of the non-scaled measurement and expressed as a percentage (Equation A.IV.1 and A.IV.2)

$$\text{RMSD} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_{\text{no scale}} - x_{\text{scaled}}\right)^2}$$

[A.IV.1]

RMSD = root mean square difference

n = number of samples

$x_{no\ scale}$ = data point without inertia scale factor

x_{scaled} = data point with inertia scale factor

$$\%\text{RMSD} = \frac{\text{RMSD}}{\text{Max}_{\text{original}} - \text{Min}_{\text{original}}} \text{ x } 100$$

[A.IV.2]

%RMSD = percentage root mean square difference

Max$_{original}$ = Maximum data point without inertia scale factor

Min$_{original}$ = Minimum data point without inertia scale factor

Results: The influence of the inertia scale factor on joint moments was less than 4%RMSD for the straddle Tkachev and longswing data. Joint powers were influenced less than 1%RMSD at the shoulder and hip joints for both skills although the knee joint powers differed by 5%RMSD. Without the inclusion of the inertia scale factor joint work was over estimated at the shoulder by 5%RMSD and at the hip by 12%RMSD. Knee joint work was under estimated by up to 57%RMSD The influence of the inertia scale factor on joint energetics was less than 1% for individual segment energy (E_{Arm}, E_{Trunk}, E_{Thigh}, E_{Shank}) and total gymnast energy.

Conclusion: Gymnasts performing the straddle longswing abduct the lower limbs at the hips and subsequently shorten the thigh and shank segment lengths modelled in the four segment representation of the gymnast. Without an inertia scale factor in place to readjust the inertia parameters to the new segment length, the joint work contributions by the lower limbs in particularly were over estimated. Remaining joint kinetic variables were marginally affected by the change in segment length and resulting inertia scale factor, with individual segment energy and total gymnast energy not affected ($\leq$1%RMSD).

APPENDIX V

THE INFLUENCE OF SEGMENTAL ENERGETIC CALCULATIONS ON TOTAL ENERGY

Introduction: Smith (1975) examined the influence of representing the human performer as a single rigid body and as a series of segments on the calculation of kinetic energy. The above author reported differences of 9% for a less dynamic landing trial and greater differences of 35% when observing more complex movements such as a standing long jump. The aim of this analysis was to determine the influence of segmental energetic calculations on the calculation of total energy during the female longswing.

Method: One International female gymnast (age 15.9 years, height 155 cm, mass 59.6 kg) performed three straddle Tkachevs and three general longswings. In order to determine the influence of segmental energetic calculations on the total kinetic energy of the gymnast, the segmental method (Equation A.V.1) similarly utilised by Arampatzis and Brüggemann (2001) was compared to the whole body representation of the gymnast (Equation A.V.2) in the calculation of total energy.

$$E_{tot} = \sum \frac{1}{2} I_i \omega_i^2 + \sum m_i \cdot g_i \cdot h_i + \sum \frac{1}{2} m_i v_i^2$$

[A.V.1]

$$E_{tot} = \frac{1}{2} I \omega^2 + m \cdot g \cdot h + \frac{1}{2} m v^2$$

[A.V.2]

E_{tot} = total energy

I = moment of inertia

ω = angular velocity

m = mass

g = acceleration due to gravity

h = height

v = linear velocity

i = i^{th} segment

Similarly to the investigation of the influence of the inertia scale factor (Appendix IV), RMSD and %RMSD were calculated to determine the differences in methods used.

Results: Total energy utilising the whole body representation of the gymnast estimated total energy during the general longswing 3%RMSD less than the segmental method (Figure A.V.1a). For the more dynamic longswing preceding the straddle Tkachev, the whole body calculation estimated total energy 5% lower than the segmental method (Figure A.V.1b). The largest differences were reported during the ascending phase of both the general longswing and the preparatory longswing where the greatest contribution to total energy by gymnast mechanical energy was expected.
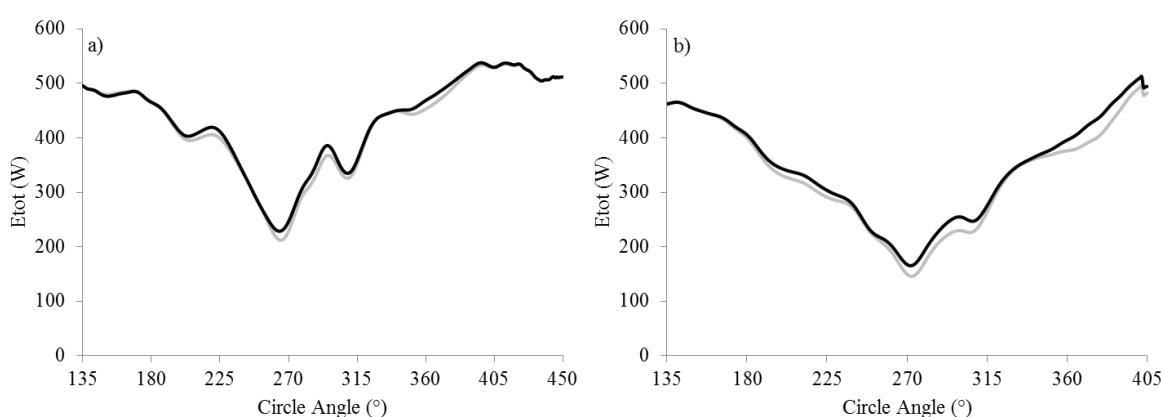
Figure A.V.1. Total energy calculated using the segmental method (black) and the whole body equivalent (grey) for the general longswing (a) and preparatory longswing preceding the straddle Tkachev (b).

Conclusion: Smith (1975) similarly reported the whole body calculation consistently estimating total energy lower than the segmental method with an increase in difference as the dynamic nature of the movement increased. The above author highlighted the importance of representing the human body as a series of rotating segments. Within Women's Artistic Gymnastics the continuous change in body positions and movement patterns supports the use of the segmental energetic calculation in the calculation of total energy.

APPENDIX VI

INDIVIDUAL TRIAL DATA FOR JOINT KINETIC AND ENERGETIC ANALYSES
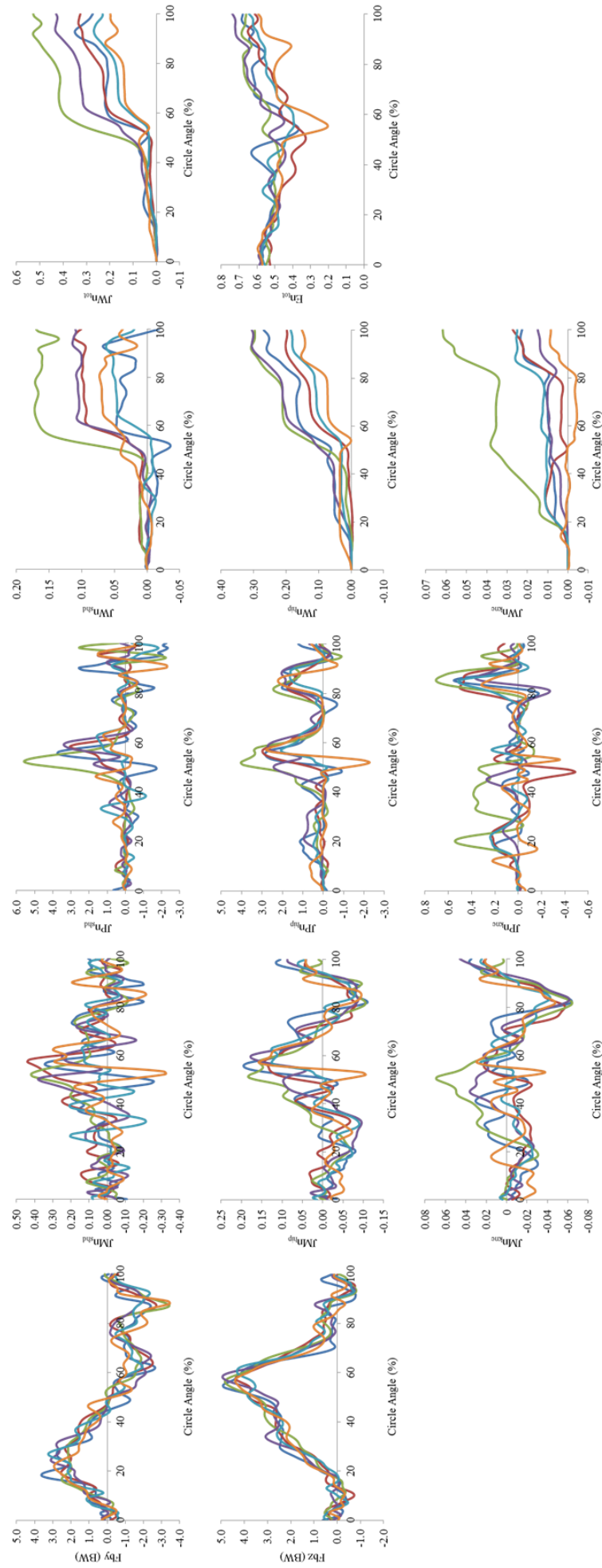

Figure A.VI.1. Arch individual trial data for estimated bar force, total joint work, total energy and shoulder and hip joint moments, joint powers and joint work.
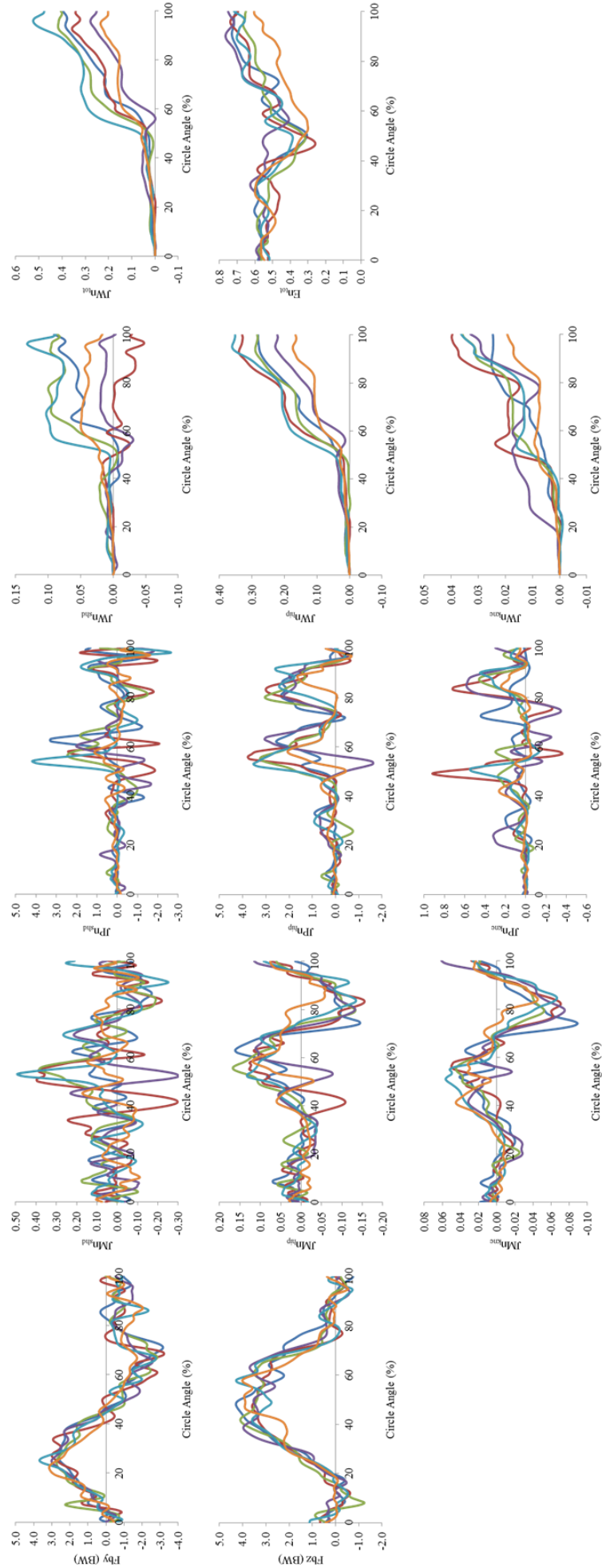
Figure A.VI.2. Straddle individual trial data for estimated bar force, total joint work, total energy and shoulder and hip joint moments, joint powers and joint work.
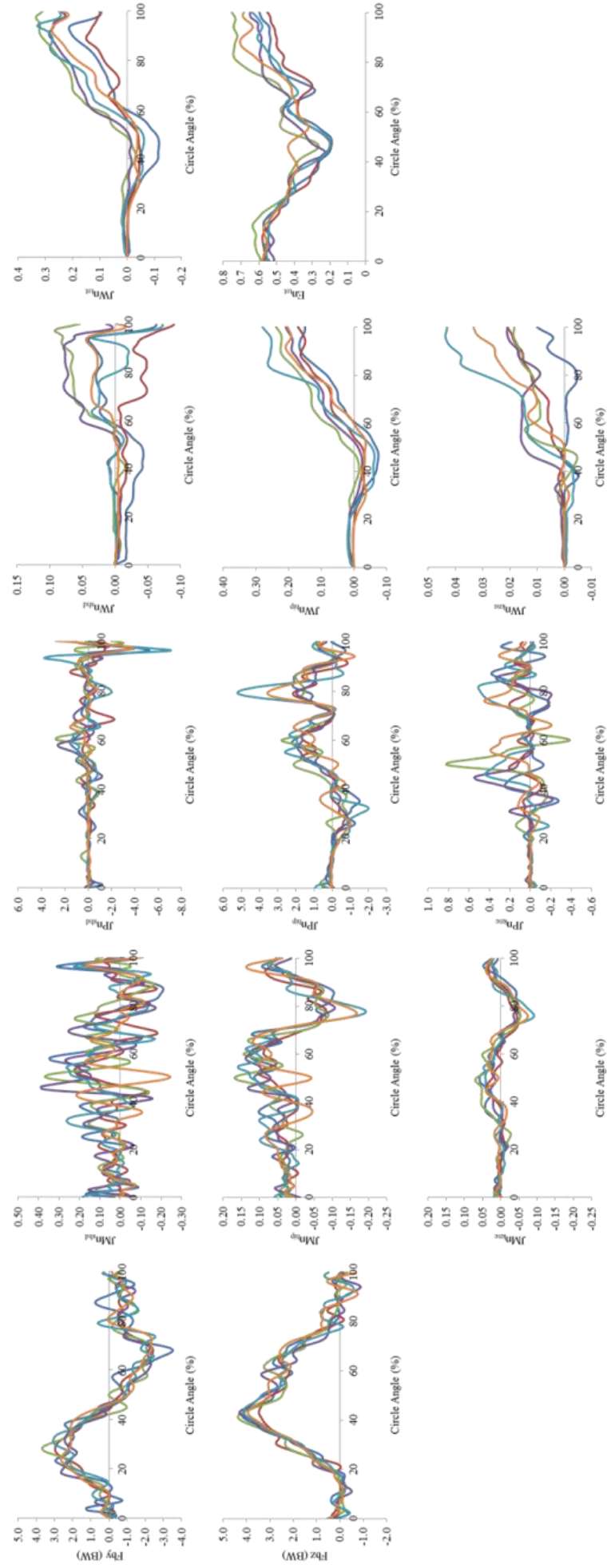
Figure A.VI.3. Pike individual trial data for estimated bar force, total joint work, total energy and shoulder and hip joint moments, joint powers and joint work.