Cardiff School of Sport

**DISSERTATION ASSESSMENT PROFORMA:**

**Empirical**

<table>
<thead>
<tr>
<th>Comments</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Student name:</strong></td>
<td>Rebecca Straker</td>
</tr>
<tr>
<td><strong>Student ID:</strong></td>
<td>st20021532</td>
</tr>
<tr>
<td><strong>Programme:</strong></td>
<td>SPE</td>
</tr>
<tr>
<td><strong>Dissertation title:</strong></td>
<td>COMPARISON OF LANDING KINEMATICS BETWEEN EXPERIENCED MALE AND FEMALE ARTISTIC GYMNASTS FOLLOWING A BACK TUCK DISMOUNT FROM THE HIGH BAR.</td>
</tr>
<tr>
<td><strong>Supervisor:</strong></td>
<td>Dr Tim Exell</td>
</tr>
</tbody>
</table>

**Title and Abstract (5%)**

Title to include: A concise indication of the research question/problem. Abstract to include: A concise summary of the empirical study undertaken.

**Introduction and literature review (25%)**

To include: outline of context (theoretical/conceptual/applied) for the question; analysis of findings of previous related research including gaps in the literature and relevant contributions; logical flow to, and clear presentation of the research problem/ question; an indication of any research expectations, (i.e., hypotheses if applicable).

**Methods and Research Design (15%)**

To include: details of the research design and justification for the methods applied; participant details; comprehensive replicable protocol.

**Results and Analysis (15%)**<sup>2</sup>

To include: description and justification of data treatment/ data analysis procedures; appropriate presentation of analysed data within text and in tables or figures; description of critical findings.

**Discussion and Conclusions (30%)**<sup>2</sup>

To include: collation of information and ideas and evaluation of those ideas relative to the extant literature/concept/theory and research question/problem; adoption of a personal position on the study by linking and combining different elements of the data reported; discussion of the real-life impact of your research findings for coaches and/or practitioners (i.e. practical implications); discussion of the limitations and a critical reflection of the approach/process adopted; and indication of potential improvements and future developments building on the study; and a conclusion which summarises the relationship between the research question and the major findings.

**Presentation (10%)**

To include: academic writing style; depth, scope and accuracy of referencing in the text and final reference list; clarity in organisation, formatting and visual presentation.

---

<sup>1</sup> This form should be used for both quantitative and qualitative dissertations. The descriptors associated with both quantitative and qualitative dissertations should be referred to by both students and markers.

<sup>2</sup> There is scope within qualitative dissertations for the RESULTS and DISCUSSION sections to be presented as a combined section followed by an appropriate CONCLUSION. The mark distribution and criteria across these two sections should be aggregated in those circumstances.
COMPARISON OF LANDING KINEMATICS BETWEEN EXPERIENCED MALE AND FEMALE ARTISTIC GYMNASTS FOLLOWING A BACK TUCK DISMOUNT FROM THE HIGH BAR.

(Dissertation submitted under the BIOMECHANICS area)

REBECCA STRAKER

ST20021532
COMPARISON OF LANDING KINEMATICS BETWEEN EXPERIENCED MALE AND FEMALE ARTISTIC GYMNASTS FOLLOWING A BACK TUCK DISMOUNT FROM THE HIGH BAR.
Certificate of student

By submitting this document, I certify that the whole of this work is the result of my individual effort, that all quotations from books and journals have been acknowledged, and that the word count given below is a true and accurate record of the words contained (omitting contents pages, acknowledgements, indices, tables, figures, plates, reference list and appendices). I further certify that the work was either deemed to not need ethical approval or was entirely within the ethical approval granted under the code entered below.

Ethical approval code:       APPR 14/5/308U
Word count:                 10,458
Name:                      Rebecca Straker
Date:                      18/03/2015

Certificate of Dissertation Supervisor responsible

I am satisfied that this work is the result of the student's own effort and was either deemed to not need ethical approval (as indicated by 'exempt' above) or was entirely within the ethical approval granted under the code entered above.

I have received dissertation verification information from this student

Name:                      
Date:                      

Notes:

The University owns the right to reprint all or part of this document.
# Table of Contents

**CHAPTER 1: INTRODUCTION**

1.0 Introduction.................................................................................................................. 2

**CHAPTER 2: LITERATURE REVIEW**

2.0 Introduction to the Literature Review........................................................................ 5

2.1 Injury Perspective in Gymnastics.............................................................................. 5

2.2 Landing Characteristics of Gymnasts...................................................................... 7

2.3 Sex Differences with Regards to Landing................................................................. 8

2.4 Coordination and Variability.................................................................................... 10

2.5 Methods of Approach............................................................................................. 11

2.6 Methods of Processing and Analysis...................................................................... 12

2.7 Summary................................................................................................................ 13

**CHAPTER 3: METHODOLOGY**

3.0 Participants.............................................................................................................. 16

3.1 Protocol.................................................................................................................... 16

3.2 Data Processing...................................................................................................... 19

3.3 Data Analysis.......................................................................................................... 20

**CHAPTER 4: RESULTS**

4.0 Results.................................................................................................................... 24

4.1 Discrete Variables................................................................................................. 24

4.2 Continuous Variables............................................................................................ 26

**CHAPTER 5: DISCUSSION**

5.0 Discussion.............................................................................................................. 35

5.1 Findings from Kinematic Data.............................................................................. 35
5.2 Coordination of the Lower Extremities ................................................................. 38
5.3 Limitations and Future Recommendations ......................................................... 39

CHAPTER 6: CONCLUSION

6.0 Conclusion .............................................................................................................. 42

REFERENCE LIST

References .................................................................................................................... 45

APPENDICES

Appendix A-Participant Information Sheet ................................................................. A-2
Appendix B-Informed Consent .................................................................................... B-2
Appendix C-Winter’s Residual Analysis .................................................................... C-2
Appendix D-The Classification of Coordination Based on Vector Coding and Angle-Angle Analysis Adapted from Chang et al. (2008) ................................................................. D-2
List of Tables

Table 1. Discrete variables ........................................................................................................... 20

Table 2. Minimum joint angles, peak joint angular velocities and maximum knee valgus angles in flexion ........................................................................................................ 25

Table 3. Angular position of the ankle, knee and hip at initial contact and the range of movement of the three joints ........................................................................................................ 25
List of Figures

Figure 1. Marker set-up for the foot used during the pilot study........................................ 17

Figure 2. System set-up for data collection........................................................................ 17

Figure 3. Marker placements for one participant.............................................................. 18

Figure 4. The continuous mean ankle angle profiles for males (black line) and females (grey line) together with the standard deviations (dashed)...............................................27

Figure 5. The continuous mean knee angle profiles for males (black line) and females (grey line) together with the standard deviations (dashed)...............................................27

Figure 6. The continuous mean hip angle profiles for males (black line) and females (grey line) together with the standard deviations (dashed)...............................................28

Figure 7. Angle-angle plots of the ankle and knee angles during landing for females and males (A. F01, B. M01, C. F02 and D. M02). The bold line represents the mean coordination pattern with individual trials (fine lines) included to illustrate variability..............................................................29

Figure 8. Angle-angle plots of the knee and hip angles during landing for females and males (A. F01, B. M01, C. F02 and D. M02). The bold line represents the mean coordination pattern for the both groups with individual trials (fine lines) included to illustrate variability..............................................................30

Figure 9. A time series profile of the resulting coupling angles (ankle and knee) for males (black line) and females (grey line)............................................................................31

Figure 10. A time series profile of the resulting coupling angles (knee and hip) for males (black line) and females (grey line)............................................................................32
Acknowledgements

Firstly and above all I would like to sincerely thank my dissertation supervisor Dr Tim Exell who has really encouraged and facilitated my learning in biomechanics, and without him I would never have achieved as much as I have this year. Secondly I would like to thank Dr Michelle Manning for her invaluable time spent helping me throughout data collection. Finally I would like to thank the gymnasts at Cardiff Metropolitan University who volunteered to participate in the study, without whom this would have all been impossible.
Abstract

Non-contact anterior cruciate ligament (ACL) injuries during dismounts have been identified as one of the most significant short and long term injuries affecting a gymnasts’ career, with females 2.4-9.7 times more vulnerable than males. Previous research has investigated dismounts and the potential of injury, however the landing height and task were disparate to any skills a gymnast would habitually perform. Therefore, the purpose of the study was to assess the kinematic landing strategies adopted by male and female gymnasts when performing a back tucked dismount from the high bar. Following ethical approval, two male and two female experienced gymnasts from Cardiff Metropolitan University volunteered to participate in the study. Two CODAmotion scanners were used to collect lower extremity kinematic data in the frontal and sagittal planes. Coordination of the lower extremities were also calculated using angle-angle and vector coding techniques. The main findings of the study identified that female gymnasts utilise larger knee and hip ranges of motion together with larger peak angular velocities of the ankle during landing. Conflicting with previous research, male gymnasts were found to land with greater lower extremity extension than females. Nevertheless both male and female gymnasts illustrated potentially harmful landing kinematics in the sagittal plane, regardless of their sex. One male gymnast emerged as the most vulnerable to ACL injuries due to the significant degrees of knee valgus demonstrated on impact. For the gymnasts included in this study, individual landing mechanics appear to be the primary cause of ACL predisposition and not biological sex differences. The coordination patterns illustrated each gymnast to have a “signature” landing style with little variability, consequentially allowing the same mechanical structures to experience overload augmenting the risk of injury. The possible harmful landing strategies adopted by gymnasts is concurrent with that of previous literature, and has been suggested to occur due to the aesthetic importance of landing in gymnastics; however the traditional sex differences often reported were not noted in this case. This study indicates the importance of appreciating gymnasts’ individual variability and not always generalising them as a population in order to avoid the possibility of debilitating injury. Furthermore the importance of a potential rule change regarding the balance between performance and injury could also be highlighted due to the lack of individual variability demonstrated on landing. These implications could be used in a training environment in order to reduce the potential risk of injury during repetitive high bar dismounts.
CHAPTER 1

INTRODUCTION
1.0 Introduction

The popularity of artistic gymnastics is ever increasing, with children as young as five participating in the sport (Bradshaw & Hume, 2012). Research has shown numerous health benefits of participating in gymnastics at such an early age, including a reduced risk of osteoporosis (Zanker et al., 2004) and other skeletal benefits such as an increase in bone mass density retained after activity cessation (Scerpella et al., 2010). However injury is not uncommon, with sprains and strains accounting for 47% to 58% of total injuries reported (Mc-Auley et al., 1987), however serious impact injuries to the neck whilst the gymnast is inverted are becoming less unusual (Sands, 2000). It has been argued that the primary goal of biomechanics should aim to prevent injuries occurring and reoccurring (McGinnis, 2013). Preatoni et al. (2012) ascertained this to be imperative for gymnasts due to the increased and repetitive biomechanical demands experienced during dismounts especially.

The study of dismounts within gymnastics has previously been, and still is a popular area of research within the biomechanics literature (Takei et al., 1992; Gervais & Dunn, 2003; Hiley & Yeadon, 2005 and Gittoes & Irwin, 2012). Artistic gymnasts are constantly subjected to a high incidence of impact landings, estimated to perform more than 200 dismounts a week (Özgüven & Berme, 1988). Dismounts in gymnastics are typically comprised of an aerial phase where the gymnast loses contact with the apparatus, and a landing phase, where they regain contact with the ground (Dufek & Bates, 1991). Marinšek, (2009) identified the ultimate objective of landing is to absorb the body’s energy generated at take-off, which is increased during flight if landing from a greater height. Together with this, gymnasts often perform multiple rotations prior to landing, contended with performing a complex rotational component in addition to landing with a safe and aesthetic double-footed landing (Gittoes & Irwin, 2012). Furthermore certain skills such as gainer layouts performed predominantly on the balance beam and floor leads the gymnast to land unilaterally, increasing the risk of injury further (Weinhandl et al., 2010).

In gymnastics there is often discordance between landing safely to reduce injury, and landing with correct technique to satisfy the sports code of points (Gittoes & Irwin, 2012). The Fédération Internationale de Gymnastique (F.I.G.) stated that if the gymnasts’ legs are apart on landing or a subsequent step is taken, a maximum of 0.8 can be deducted from their individual score (FIG., 2013). To coincide with the correct practices the gymnast must land complex skills with both feet simultaneously together. Gianotti, Hume & Tunstall
(2010) have suggested ideal biomechanical landing technique in netball and soccer to involve landing with the feet shoulder width apart in order to reduce the risk of injury, however this would be contradictory in gymnastics if the gymnast was to satisfy the sports’ code of points.

Hunter & Torgan (1983) suggested a change needed to be made regarding the scoring of gymnastic dismounts. They proposed a lower percentage of the score to be contributed to the dismount, in order to discourage gymnasts from performing more difficult landings and reduce injury rates. Mc-Auley et al. (1987) alluded to the fact that skilled coaches would undoubtedly disagree, as they believe difficulty in dismounts to be an integral part of the sport. Therefore due to the high injury rates and complex landing techniques employed it seems a biomechanical factor regarding the actual landing mechanics that need to be explored.

Within the literature gymnasts already appear to be predisposed to lower extremity injuries due to the nature (Sabick et al., 2006) and sheer frequency of landings (Gittoes & Irwin, 2012). Taking this previous literature into consideration, female gymnasts appeared to be the most susceptible to injury upon landing, compared to male gymnasts. However, little research has been implemented to identify differences in landing kinematics between male and female gymnasts, in order to aid in the understanding of the increased occurrence of injuries in female gymnasts compared to males, whilst still performing the same skill.
CHAPTER 2

LITERATURE REVIEW
2.0 Introduction to the Literature Review

The following chapter comprises of a review of the literature regarding the prevalence of injuries within gymnastics, in particular dismounts from the high bar, in addition to an appraisal of the often vulnerable landing characteristics of gymnasts and female athletes. Finally a review of the selected methodological processes used to collect, process and analyse data is included.

2.1 Injury Perspective in Gymnastics

2.1.1 Injury in Gymnastic Dismounts

The dismount is a significant component of a gymnastics routine. Not only is it the ultimate movement for every routine, it is the last element of the movement sequence that will retain in the judges memory before scores are awarded (Gervais & Dunn, 2003). Although arguably an integral part of the sport, the encouragement of complex dismounts when the gymnast is most fatigued is suggested to lead to injury (Hunter & Torgan, 1987), due to most dismounts including landings from a large height (5 times the gymnast’s height).

Caine et al. (1989) noted that 36% of all injuries sustained by young competitive gymnasts occurred during dismounts, with Meeusen & Borms (1992) identifying the lower extremities to be the most affected. Devita & Skelly (1992) suggested the considerable impact forces experienced during landing could be a contributor to the substantial number of lower extremity injuries.

Within the biomechanical literature regarding universal sports landings, double back somersaults performed by gymnasts on the floor apparatus appeared to result in the highest peak landing forces normalised by body weight, ranging from 8.8-18.0 VGRF/BW, essentially predisposing them to a higher possibility of lower extremity injury (Bressel & Cronin, 2005).

2.1.2 Injury Perspectives on Gymnastic Apparatus

Previous research has acknowledged the floor and tumbling exercises to exhibit the highest rate of injuries (38%) hypothesised to be because of the extensive time gymnasts train on the floor compared to other apparatus (Garrick & Requa, 1980). Ankle sprains have been identified as the predominant injury during floor and tumbling exercises as a result of hyperextension (Grapton et al., 2013). This is thought to be caused by the under rotation of saltos as a consequence of the axis of rotation, the increased number of turns
and the initial landing height (Marinšek & Cuk, 2010). In the literature the uneven bars have reported a much higher incidence of chronic knee injuries due to excessive repetitive load being placed on these areas during dismounts (Stephen et al., 2007). Unlike performances on the floor the uneven bar dismount has to reduce the bodies’ vertical, horizontal and angular momentum to zero, without moving the feet from a substantially greater height (McNitt-Gray, 2000). The ability of the gymnast to constantly resist extreme ground reaction forces whilst ‘sticking’ the landing has been recognised as a contributor to lower extremity overuse injuries (Zhang et al., 2000). However there are also circumstances where female gymnasts in particular, may experience an unfortunate coupling of musculoskeletal and hormonal structures and functions that lead to sudden and acute anterior cruciate ligament (ACL) tears during landing (Wild et al., 2012). Sands et al. (2004) found the uneven bars to generate the most injuries out of all apparatus throughout one season. However it was noted by the authors to consider the inter-variability and intra-variability of gymnasts in terms of their responses to movement constraints (Bernstein, 1967). The variability of gymnasts to particular tasks and environments could have potentially lead to the discrepancy between studies.

### 2.1.3 Injury Perspectives on Bar Apparatus

Both male and female elite, artistic gymnasts perform on a piece of apparatus involving one or two bars. Women perform on the asymmetric bars, with the tallest bar 2.50m high, whilst men perform on the parallel bars and the high bar, with heights of 2.55m and 2.80m respectively (FIG., 2013).

Studies of horizontal bar dismounts have received a reasonable amount of attention over the years due to the characteristics of uneven bar performances (Caine et al., 1989) and the often unsuccessful landings of high bar performances (McNitt-Gray et al., 1998). Takei et al. (1992) believed dismounting from the high bar to result in the most serious injuries in gymnastics due to the multiple rotations often being performed from a considerable height prior to landing.

Marinšek (2009) proposed that a higher flight phase resulted in a higher vertical ground reaction force upon landing. An increase in skill complexity has been associated with an increased height (King et al., 1999) with greater vertical velocity at release augmenting the height and time in which to perform that skill (Irwin et al., 2014). Ground impact forces are said to be greater with an increase in drop height (Dufek and Bates, 1991) leading to a higher potential for injury (Mills et al., 2009). The landing characteristics of gymnasts have
been recognised as a factor influencing this. Gittoes et al. (2013) coincided with this, suggesting forces experienced on landing to be influenced by kinematic landing strategies. An absence of research into dismounts from the uneven bars has been discerned in particular, in addition to analysed kinematic landing techniques by female gymnasts from this particular piece of apparatus (Prassas, 1996). It was recognised that similarities in kinematics may exist between the dismounts from the high bar and uneven bars; however differences should be expected because of the variation in design and construction of the apparatuses. Since this early research, the uneven bars have evolved (Normile, 2008) increasing by 0.1m in height and 0.4m between the rails (FIG., 2013) exposing a gap in the literature. In previous research a meta-analysis has been conducted to compare the primary female kinematic landing data from the uneven bars to secondary male kinematic landing data from the high bar in other previous studies. This process loses reliability as the secondary data has already been manipulated by human biases (Dunsmuir & Williams, 1992).

2.2 Landing Characteristics of Gymnasts

Unique to countless other sports, landings in gymnastics take into account both aesthetic and safety aspects (Gittoes & Irwin, 2012), in addition to a judge awarding superiorly executed performances with higher marks, in accordance with the code of points (FIG., 2013). As already previously stated, gymnastic dismounts frequently require multiple rotations and often other skills are performed sequentially (Gittoes & Irwin, 2012) arguably augmenting the risk of injury compared to other sports.

McNitt-Gray (1991) compared landing techniques of male collegiate gymnasts and recreational athletes from drop heights of 0.32, 0.72 and 1.82m providing impact velocities of 2.5, 3.75 and 5.0m/s respectively. This was to replicate typical velocities experienced by gymnasts on the pommel horse, balance beam and floor exercise. Due to the athletes landing bare foot onto no gymnastics mats, the extreme velocities often experienced on the high bar were excluded. The results indicated male gymnasts to land with significantly less joint flexion in the sagittal plane than the recreational athletes, suggesting reduced sensitivity by gymnasts to greater impact velocities. Although proposing a potential increase in injury to male gymnasts as a population, it is important to appreciate female gymnasts who perform on the balance beam, and the conceivable effect it could have on their landing kinematics.
Later research by McNitt-Gray et al. (1993) involved a similar protocol, however examined drop landings involving intercollegiate female gymnasts alone. The heights were similar to earlier research of 0.69, 1.25 and 1.82m, with 1.82m selected to reproduce similar velocities experienced dismounting from the uneven bars. The aim of the study was to investigate the preferred landing strategies to reduce the potential for injury. The results found the participants experiencing up to 9 times the body weight upon impact from a drop of 1.82m, suggested to be due to insufficient joint flexion (Gross & Nelson, 1988); in turn characterising gymnasts to have a stiff landing. Devita & Skelly (1992) defined a stiff landing of maximum knee flexion angles less than 90 degrees from full extension. Zatitorny & Prilutsky (1987) reported stiff landings to increase the chances of injury due to passive structures experiencing greater energy absorption. Although the drop height was applicable to gymnastics in all protocols, it is very rare for a gymnast to dismount without any rotation in the sagittal plane (Gittoes & Irwin, 2012).

It was alluded to in the reviewed literature therefore that repetitive loads together with landing kinematics that increased the risk of injury in gymnasts. The suggestion made by researchers was to reduce the impact load on landing by changing landing technique. Kovács et al. (1999) identified a greater peak ground reaction force on impact during a heel-toe landing than a fore-foot landing, increasing the potential for soft tissue injury. Thereby to reduce the load imposed on the ACL, gymnasts should consider landing on the forefoot and rolling onto the heel (Renstrom et al., 2008). However this is not always possible during rotated dismounts in gymnastics (McNitt-Gray, 1991).

2.3 Sex Differences with Regards to Landing

Various retrospective studies have sought to compare sex differences on landing between male and female volleyball (Ferretti et al., 1992) soccer and basketball players (Arendt & Dick, 1995). All studies showed a higher potential of lower extremity injuries to affect the female participants, disclosing them as a more vulnerable population. Although these retrospective studies provided data highlighting female athletes experiencing a higher rate of injuries and how they happened, they did not look into the possible landing kinematic and kinetic differences between male and female athletes.

Latter research by Decker et al. (2003) investigated the sex differences in lower extremity kinematics, kinetics and energy absorption during landing of volleyball and basketball players. It was found that females landed with a more erect posture than males, utilising greater joint ranges of motion at the hip and ankle with greater maximum angular
velocities. Both males and females applied the knee as the primary shock absorber in terms of magnitude and timing, however the ankle plantar-flexors were acknowledged to be the secondary shock absorber for females and hip extensors for males. It was inferred that because the female athletes had the tendency to use the ankle to absorb a greater amount of the impact forces, together with landing with greater knee extension presented a harmful landing strategy. Decker and colleagues presented a study which could be used to facilitate a change in landing technique used by female athletes. However the drop landings were not entirely sport specific to the landings normally encountered by the athletes in basketball or volleyball.

Salci et al. (2004) therefore investigated landing manoeuvres between male and female volleyball players using landing techniques more replicable to that of skills performed in their sports. Similar to Decker et al. (2003) female athletes landed with significantly lower knee and hip flexion angles compared to the male athletes suggested to increase peak ground reaction forces (VGRF). However it was acknowledged by latter research that it is not necessarily smaller knee and hip flexion angles that increase impact forces but that of the angular velocity of the knee on initial contact (Yu et al., 2006). An abundance of research was being gathered in volleyball and basketball, however little had been completed in sports such as gymnastics, particularly focusing on frontal mechanics.

Further research was recommended to concentrate on sports such as gymnastics where little previous research on landing mechanics had been reported (Yu et al., 2006). Cortes et al. (2007) found no significant difference in time instants of initial contact, peak vertical ground reaction force and maximum knee flexion angles between male and female gymnasts on a simple drop landing task. It was hypothesised that this could be due to the task being too simple for normal landing patterns and the landing height to be unrepresentative of normal sporting behaviours (Cortes et al., 2007). Russell et al. (2006) concurred with this finding little significant difference of lower extremity kinematics between male and female athletes, however suggested to be because sex disparities are more noticeable in the frontal plane of movement.

Various researchers have identified female athletes to exhibit greater knee valgus during sporting movements (Ford et al., 2003; Hewett et al., 2005; Hughes, Watkins & Owen, 2008), highlighted to create a greater predisposition to ACL injury. However more recently Bruton et al. (2013) have reported sex differences within sporting movements to decrease as skill expertise increases. Rotated dismounts from the high bar were selected for
analysis due to the inclusion of the largest landing height of apparatus competed on by male and female gymnasts. Nonetheless the use of more experienced gymnasts in this study performing an identical skill, may reveal fewer sex disparities than one may expect (Bruton et al., 2013).

Research comparing landing mechanics between male and female athletes is a popular area of research (Ferretti et al., 1992; Arendt & Dick, 1995; Decker et al., 2003; Salci et al., 2004; Cortes et al., 2007; Schmitz et al., 2007). With female athletes emerging to be most susceptible to injury when landing, it is of value to understand the landing mechanics of both male and female athletes. Understanding the differences between male and female gymnasts during landing may aid in the prevention of injury during dismounts from bar apparatus. Little research has been conducted regarding the differences in landing kinematics between male and female gymnasts, using landing heights and actions with any ecological validity. Countless research concerning landing mechanics has involved step drop landings from a platform (McNitt-Gray, 1991; McNitt-Gray et al., 1993; McNitt-Gray et al., 1994; Decker et al., 2003). However none have replicated realistic training environments during landing often due to controlling variables in order to maintain reliability (Schmuckler, 2001), and so lose ecological validity that sports practitioners expect (Bartlett, 2008). Nevertheless in gymnastics where technique corresponds to performance (FIG., 2013) many variables can be controlled that do not affect the reliability of the study and uphold ecological validity, overcoming this problem posed by Bartlett (2008). This is of value as other research has indicated female athletes to be a potentially more vulnerable population when landing. Therefore implications from this study could be used to inform injury prevention within a coaching-biomechanics interface (Irwin et al., 2014).

2.4 Coordination and Variability

According to the Dynamical Systems Theory effective self-organisation of the numerous degrees of freedom is necessary to execute healthy and functional human movement patterns (Bernstein, 1967). Successful human movement patterns are therefore described as the individual muscles and neuropathways operating effectively together, to attain an outcome meeting the constraints of the system (Kurz & Stergiou, 2004). Variations in the manner that degrees of freedom are coordinated together, provide a reasoning to why no two movements are identical (Kurz & Stergiou, 2004), yet still may serve some sort of functionality in human movement (Bartlett et al., 2007).
Previous literature has considered stiff landings as a disadvantageous landing strategy, reporting the muscular system to absorb more kinetic energy during soft landings, so relieving impact stress on other body tissues (Devita & Skelly, 1992; Hauschildt, 2008). Although female gymnasts have been identified as a population exhibiting the stiff landing strategy, it is of value to consider the distinctiveness of gymnastics and the role of variability and coordination within subjects to meet the constraints of the particular task (Irwin & Kerwin, 2009).

The current literature on variability and coordination in sports movements is relatively small due to variability within human movement always thought to be noise and a limiting factor to motor control (Newell & Corcos, 1993). However with variability now being understood to have some sort of functionality within clinical biomechanics (van Emmerik & van Wegen, 2000) perhaps the coordination strategies displayed within female gymnasts during landing is depicting a functional role. Female gymnasts may execute landings in this particular manner to cope with the constraints being placed upon them, perhaps using one coordination pattern to relieve the stress on another mechanical structure. In addition to this female athletes have been recognised as a population lacking movement variability (Pollard et al., 2005). Insufficient variability of coordination and movement patterns can allow excessive and repetitive loads to be placed on the same mechanical structures causing injury (Pollard et al., 2005).

2.5 Methods of Approach

2.5.1 Research Design

For quantitative studies a sample of 30 participants has been recommended in order for basic descriptive statistics to be calculated (Gratton & Jones, 2010), as to ensure the results reflect a true representation of the general population (Mullineaux et al., 2001). More recently however there has been some discourse in the use of single-subject analysis over traditional group statistical analysis within human movement studies (Bates et al., 2004). Group statistical analyses seek generalizability, constantly searching for “average” results from “average” individuals, however the idea that there are any genuine average individuals seems improbable (Sidman, 1960). Using more experienced performers in this study to execute a closed skill with near identical environmental conditions, allowed for the environmental and task constraints to be kept to the bare minimum. This permitted for the inter-subject variability to be explained through individual response patterns employed by athletes due to their own biological structure (Bates et al.,
Therefore a single-subject design was used to facilitate in the understanding of potentially unique landing characteristics often exhibited by male and female gymnasts, and if they express any similar kinematic landing patterns in an ecologically valid study (Bates et al., 2004).

2.5.2 Data Collection Processes/Motion Analysis

Motion capture systems have developed significantly since the late 1960’s (Winter, 2009), with automated motion capture systems becoming the preferred choice over digital video capture in laboratory settings (Robertson et al., 2014). Digital video capture is still utilised in field-based settings when it is not possible to apply markers to an athlete (Elliot et al., 2007). However due to the laborious task of manually digitising the coordinates and the increased accuracy of automated systems (Richards, 1999), is not the favoured imaging system used in laboratories. Automated systems are the preferential choice in current motion capture in biomechanics, consisting of two main types, either passive systems that use reflective infrared light (VICON) or active systems such as CODA that use infrared light-emitting diodes to recognise marker positions. Both systems are able to digitise 3D coordinates of movement data automatically and quickly, becoming more valuable in terms of efficiency (Robertson et al., 2014).

2.6 Methods of Processing and Analysis.

2.6.1 Filtering

Smoothing and filtering digital data is a customary technique used in sports biomechanics studies in order to eliminate the noise or variability throughout the data set, but leave the true signal unaltered (Derrick, 2014). Derrick (2014) identified the two most regularly used in sports biomechanics. High-pass filters that attenuate low frequencies and leave higher frequencies unaffected and vice versa for low-pass filters. High-pass and low-pass filters are often used to filter out noise in digitised kinematic data and movement artifacts in electromyographic data respectively. Sports biomechanics has previously regarded this noise as detrimental to performance and removed from data as a source of error (van Emmerik et al., 2014). More recently researchers have started to acknowledge this noise or variability to serve some sort of functionality (van Emmerik & van Wegen, 2000; van Emmerik et al., 2014). Therefore Winter’s residual analysis (2009) was used in order to acquire the optimum cut-off frequency between noise reduction and signal attenuation (van Emmerik et al., 2014).
2.6.2 Kinematic Analyses

Previous research exploring landing kinematics have captured and analysed lower extremity joint flexion, angular velocities and range of movement in the sagittal plane (McNitt-Gray 1991; McNitt-Gray et al., 1993; Decker et al., 2003). Although a well-established method for identifying key injury factors, Russell et al. (2006) suggested sex differences with regards to landing technique to be more evident in the frontal plane of movement, such as knee valgus angles.

Traditional analytical methods applied in sports biomechanics often examine discrete or continuous measures of conventional Newtonian mechanics of a single joint or segment against time series data (van Emmerik et al., 2014). These methods are widespread in biomechanics and do serve a purpose when analysing movement data in terms of injury and performance predictors (McNitt-Gray 1991; Decker et al., 2003). However more recent analytical methods from a dynamical systems perspective centre the emphasis on the coordination of joints or segments to produce patterns of motion as significant indicators of performance or injury (van Emmerik et al., 2014).

Angle-angle diagrams graph the angular movement of one segment against another, offering a method of representing coordination between the two variables (Hamill et al., 2000). However quantifying coordination was further suggested to ease the interpretation and assessment of coordination through vector coding. Vector coding and continuous relative phase (CRP) were methods introduced to facilitate and enhance the interpretation of coordination (Tepavac & Field-Fote, 2002). Although CRP has been established as the next step of quantifying coordination as it takes into account both the rate and position of moving limbs, it was deemed inappropriate for this study because of the non-sinusoidal nature of the joint kinematics (Peters et al., 2003). To facilitate in the interpretation of vector coding the coupling angles were divided into bins, where in phase equates to both joints flexing or extending and anti phase equates to one joint flexing and the other extending (Chang et al., 2008) (see Appendix D).

2.7 Summary

Through the literature it appears that gymnasts are highly susceptible to injury (McNitt-Gray et al., 1993; Seegmiller & McCaw, 2003; Mills et al., 2009) potentially due to the nature of the sport. Female athletes however have also emerged as a vulnerable population in terms of injury on landing compared to males (Kirialanis et al., 2002; Decker
et al., 2003; Salci et al., 2004; Schmitz et al., 2007), hypothesised to be as a result of anatomical or functional differences between male and female athletes. Female gymnasts have been acknowledged as the most susceptible population when it comes to injury on landing, however little research has been done comparing landing kinematics of male and female gymnasts. Additionally with the development of bar apparatus and the increasing difficulty of skills being performed, the high bar and uneven bars have been identified as high risk apparatuses for injury (Takei et al., 1992).

Therefore the aim of this study was to compare the landing techniques between male and female artistic gymnasts following a back tuck dismount from the high bar. The purpose of which could inform training and reduce injury potential.
CHAPTER 3

METHODOLOGY
3.0 Participants

Four participants, two male (age: 19±0.4 years; height: 177.5±0.7 cm; mass: 67.2±5.2 kg; and experience: 10.5±2.1 years) and two female gymnasts (age: 21.8±0.3 years; height: 167.0±0.0 cm; mass: 58.9±1.2 kg; and experience: 10.5±0.7 years) who were training at least three times a week and were free of injury from Cardiff Metropolitan University gymnastics team volunteered to partake in the study. Each gymnast was required to complete a well-executed back tucked dismount from the high bar, and land with a safe and aesthetic landing style. A requirement of all gymnasts participating in the study was to have competed at county level or higher to perform the skill at a satisfactory level, in accordance with the marking criteria specified in the code of points (FIG, 2013). A qualified level 2 gymnastics coach was also present to ensure maximum safety to all those taking part. Prior to agreeing to take part all participants were given a participant information sheet (Appendix A) regarding the protocol and what is expected of them. Those prepared to take part subsequently gave written informed consent for the study (Appendix B). All ethical approval was acquired through the University’s Research Ethics Committee.

3.1 Protocol

3.1.1. Pilot Study

Preceding any formal data collection, a pilot study was implemented to establish the most suitable method used for collection. Two Cartesian Optoelectric Dynamic Anthropometers (CODA) were chosen as the most appropriate system to gather data from active markers placed unilaterally on the participants’ body (see full details in 3.2.2). Accordingly the main objectives of the pilot study were to: (i) determine the visibility of joint markers (ii) establish the equipment set-up (iii) develop a method of defining touchdown without the use of a force plate.

The pilot study indicated potential problems with the marker placement on the fifth metatarsal phalange (MTP) joint centre in addition to defining the instant of touchdown. To meet the safety requirements, crash mats were placed for gymnasts to land on, however this created difficulty in measuring the foot and ankle kinematics due to the lost visibility of the markers. To overcome this the foot was defined by placing a marker on the calcaneus and the tuberosity of the second metatarsal (see Figure 1). Losing the visibility of the MTP marker created additional difficulty in defining the instant of touchdown.
Devoid of a force platform with additional difficulties of MTP marker visibility, a novel method of defining the instant of touchdown was developed based on a technique applied in the analysis of sprint running (Bezodis et al., 2007). Four markers were placed on the corners of the landing mat so when the gymnast landed, the mat subsequently compressed towards the middle, accelerating the outside markers upwards. Touchdown was therefore defined as the time point when the markers reached peak vertical acceleration.

Figure 1. Marker set-up for the foot used during the pilot study

3.1.2 Data Collection

The system set-up for the data collection trials is displayed in Figure 2. Two CODA units sampling at 200Hz (Charnwood Dynamics Ltd., Leicestershire, UK) were used to collect the kinematic data for individual trials. The two scanners were placed perpendicular to the landing area to capture the whole movement from when the gymnast released the bar to the end of landing.

Figure 2. System set-up for data collection.
Five active cx1 CODA markers were placed unilaterally on the left hand side of each gymnast’s body, similar to that illustrated in Figure 3, to capture lower extremity joint kinematics. The participants were required to attend data collection wearing leotards and shorts, not only because this is what is most normal to them, but also facilitated in the reduction of noise caused by loose clothing. After all kinematic data were collected, the gymnasts’ height and mass were collected using a Harpenden 602 stadiometer (Holtain Ltd, Pembrokeshire, UK) and a set of Seca 7701321004 scales (Seca, Hamburg, Germany).

![Figure 3. Marker placements for one participant.](image)

Before any data collection, the gymnasts were given the opportunity to perform their own warm up, similar to what they would normally do prior to training. Each gymnast was then asked to execute a back tucked dismount from the high bar as a test trial to familiarise them with the testing method and to attain the visibility of markers on landing.

During formal data collection the male participants were instructed to perform five successful back tucked dismounts from a metal high bar and the women from a wooden bar as this is the apparatus performed on by each gender in competition (FIG., 2013). However the high bar was set at 2.80m (competition height for men) for both male and female participants as this is what they trained on and felt comfortable in addition to controlling for the effects of bar height on landing technique. All landings were executed onto a crash mat that is commonly used for the practice of the skill in training (Figure 2). A
successful landing was defined as a safe and aesthetic double footed landing, with all the markers being in view of the scanners during impact.

3.2 Data Processing

The 2-Dimensional marker positions were passed through Winter’s Residual Analysis (2009) using a modified recursive Butterworth filter to reduce the noise present in the raw data. The optimum cut-off frequency was ascertained to be 13 Hz (Appendix C). The optimum cut-off frequency was determined through residual analyses on four trials; one for each participant, chosen at random. Only the landing data was chosen for processing as this was the movement phase of most interest for analysis.

The lower extremity joints of most interest were defined in CODA by generating angles between the marker positions. The ankle joint created between the MTP, ankle and knee marker positions, expressed full plantar flexion in the sagittal plane at 180° with a decreasing value representing dorsi flexion. The knee and hip joints demonstrated full extension in the sagittal plane of 180° with any decreasing value also representing flexion. The knee joint was created using the ankle, knee and hip markers, and the hip joint was generated using the knee, hip and shoulder markers. Frontal plane knee angles were created between the ankle, knee and hip markers, with valgus angles abducting and varus angles adducting from the central line of the body.

The instant of touchdown was defined as the peak upward acceleration of the mat markers, and recognised as the start of landing. The end of landing was defined as the maximum angle of knee extension.
### 3.3 Data Analysis

#### 3.3.1 Discrete Variables

**Table 1: Discrete variables**

<table>
<thead>
<tr>
<th>Discrete variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum joint angles (hip, knee and ankle)</td>
<td>Sagittal joint angles were defined; a graph was generated of vector angles over time. This data was transferred to MSexcel where the minimum joint angles were identified for each participant</td>
</tr>
<tr>
<td>Peak joint angular velocities in flexion (hip, knee and ankle)</td>
<td>Sagittal joint angles were defined; a graph was generated for joint angular velocities over time. The data was transferred to excel where the mean peak angular velocities for each participant were identified</td>
</tr>
<tr>
<td>Angular position of the lower extremity joints at contact (hip, knee and ankle)</td>
<td>From the sagittal joint angle data already transferred to excel, the first angle recorded at initial contact was identified for each participant</td>
</tr>
<tr>
<td>Range of movement (hip, knee and ankle)</td>
<td>From the sagittal joint angle data already transferred to excel, the minimum joint angle was subtracted from the maximum joint angle to obtain the range of movement for each participant</td>
</tr>
<tr>
<td>Maximum valgus angle (knee)</td>
<td>Frontal knee angles were defined in CODA; a graph of frontal knee angle over time was generated and transferred to excel. Where the maximum knee valgus angle was identified for each participant</td>
</tr>
</tbody>
</table>
All discrete variables were selected based on key variables identified by previous research as potential features of harmful landing strategies (McNitt-Gray, 1991; Decker et al., 2003; Russell et al., 2006; Cortes et al., 2007; Weinhandl et al., 2010).

To determine the differences within sexes, a mean response was calculated for each discrete variable for males and females. The variability within these discrete values was further calculated using the coefficient of variation (CV):

\[
\text{Coefficient of variation (\%)} = \frac{s}{x} \times 100
\]

\(s = \text{standard deviation}\)

\(x = \text{mean}\)

The mean of each joint was determined as an overall average of every trial within the particular sex groups, with the standard deviation calculated similarly.

3.3.2 Continuous Variables

The continuous variables chosen for analysis were angle and angular velocity kinematic profiles which were created in excel from data collected by CODA. Before being exported to excel each landing data set was normalised to 100% of movement time, so that continuous data could be compared across trials and participants. The root mean squared (RMSD) value was calculated in order to quantify the continuous data and compare means between the groups.

Intra-limb coordination of the ankle, knee and hip movements during landing were calculated using vector coding techniques (Hamill et al., 2000; Heiderscheit et al., 2002). Two individual angle-angle diagrams were constructed for interactions between the ankle and knee and the knee and hip. The resultant angle (\(\phi\)) was further calculated using the equation below:

\[
\phi = \tan^{-1}(\frac{y_{i+1} - y_i}{x_{i+1} - x_i})
\]

Where \(\phi = \text{resultant angle}; i = \text{data point 1, 2, ..., n}; x = \text{angle 1} \text{ and } y = \text{angle 2.} \)
In order to quantify coordination further, the coupling angles were divided into “bins” to facilitate the interpretation of coordination diagrams (see Appendix D) (Chang et al., 2008).
CHAPTER 4

RESULTS
4.0 Results

A table (Table 2) of minimum joint flexion angles, peak joint angular velocities and maximum knee valgus angles are presented to demonstrate the differences in kinematics between groups and individuals during landing. A second table (Table 3) of the angular position of the joints at initial ground contact and the range of movement of the same joints are displayed to identify the differences in kinematics at the start and throughout landing. The coefficient of variation (CV) is included for each discrete variable denoting the amount of intra-variability between trials for each participant and between males and females as a group.

4.1 Discrete Variables

4.1.1 Minimum Joint Flexion Angles

The minimum joint angles during flexion signified the two male gymnasts to generally land with a greater amount of knee and hip extension (126.5° and 129.7°) than the female gymnasts (104.8° and 110.7°). However the female gymnasts landed with less ankle flexion than their male counterparts of 77.6° and 78.3° respectively. Low amounts of variability were exhibited in all joints by F02, the knee in F01 and the ankle of M01 (CV<10%).

4.1.2 Peak Joint Angular Velocities in Flexion

The peak angular velocities in flexion display the largest amount of variability in individuals and groups. Female gymnasts displayed a tendency to land with greater peak angular velocities of the ankle, knee and hip (-455.1°.s⁻¹,-427.4°.s⁻¹ and -246.7°.s⁻¹) compared to the male gymnasts (-263.4°.s⁻¹,-291.9°.s⁻¹ and -216.3°.s⁻¹). All joints across all individuals and groups demonstrated a large coefficient of variability (CV>10%).

4.1.3 Angular position of the lower extremity joints at contact

The angular position of the lower extremity joints at initial joint contact presented similar results across individual trials. There was a small difference in ankle, knee and hip initial ground contact angle of 7.0°, 1.5° and 2.5° between male and female gymnasts respectively. Females demonstrated a greater degree of extension of the ankle and knee at initial ground contact whereas males showed a greater degree of extension at the hip. A slightly larger difference was found across individuals with a 22.4°, 17.6° and 13.8° difference in ankle, knee and hip respectively. However only the mean hip angles
displayed by both males and the ankle angle by M01 indicated higher amounts of variability (CV>10%).
Table 2. Minimum joint angles, peak joint angular velocities and maximum knee valgus angles in flexion.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Joint</th>
<th>F01</th>
<th></th>
<th>M01</th>
<th></th>
<th>F02</th>
<th></th>
<th>M02</th>
<th></th>
<th>Male</th>
<th></th>
<th>Female</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean±SD</td>
<td>CV(%)</td>
<td>Mean±SD</td>
<td>CV(%)</td>
<td>Mean±SD</td>
<td>CV(%)</td>
<td>Mean±SD</td>
<td>CV(%)</td>
<td>Mean±SD</td>
<td>CV(%)</td>
<td>Mean±SD</td>
<td>CV(%)</td>
</tr>
<tr>
<td>Minimum Joint Angle (°)</td>
<td>Hip</td>
<td>103±17</td>
<td>17</td>
<td>131±14</td>
<td>11</td>
<td>119±3</td>
<td>2</td>
<td>128±19</td>
<td>15</td>
<td>130±16</td>
<td>12</td>
<td>111±15</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Knee</td>
<td>98±7</td>
<td>7</td>
<td>126±14</td>
<td>11</td>
<td>112±9</td>
<td>8</td>
<td>127±18</td>
<td>14</td>
<td>127±15</td>
<td>12</td>
<td>105±11</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Ankle</td>
<td>77±9</td>
<td>12</td>
<td>90±3</td>
<td>4</td>
<td>79±6</td>
<td>8</td>
<td>66±11</td>
<td>16</td>
<td>78±15</td>
<td>19</td>
<td>78±7</td>
<td>10</td>
</tr>
<tr>
<td>Peak Joint Angular Velocity (°.s⁻¹)</td>
<td>Hip</td>
<td>-285±48</td>
<td>17</td>
<td>-72±46</td>
<td>64</td>
<td>-208±140</td>
<td>68</td>
<td>-332±94</td>
<td>29</td>
<td>-216±155</td>
<td>72</td>
<td>-247±107</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>Knee</td>
<td>-511±97</td>
<td>19</td>
<td>-424±154</td>
<td>36</td>
<td>-344±219</td>
<td>64</td>
<td>-160±52</td>
<td>33</td>
<td>-292±176</td>
<td>60</td>
<td>-427±183</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>Ankle</td>
<td>-456±185</td>
<td>41</td>
<td>-209±56</td>
<td>27</td>
<td>-454±182</td>
<td>40</td>
<td>-317±276</td>
<td>87</td>
<td>-263±196</td>
<td>74</td>
<td>-455±173</td>
<td>38</td>
</tr>
<tr>
<td>Maximum Valgus Angle (°)</td>
<td>Knee</td>
<td>13±4</td>
<td>34</td>
<td>24±7</td>
<td>28</td>
<td>15±2</td>
<td>10</td>
<td>10±5</td>
<td>44</td>
<td>17±9</td>
<td>53</td>
<td>14±3</td>
<td>24</td>
</tr>
</tbody>
</table>

Table 3. Angular position of the ankle, knee and hip at initial contact and the range of movement of the three joints.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Joint</th>
<th>F01</th>
<th></th>
<th>M01</th>
<th></th>
<th>F02</th>
<th></th>
<th>M02</th>
<th></th>
<th>Male</th>
<th></th>
<th>Female</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean±SD</td>
<td>CV(%)</td>
<td>Mean±SD</td>
<td>CV(%)</td>
<td>Mean±SD</td>
<td>CV(%)</td>
<td>Mean±SD</td>
<td>CV(%)</td>
<td>Mean±SD</td>
<td>CV(%)</td>
<td>Mean±SD</td>
<td>CV(%)</td>
</tr>
<tr>
<td>Angular Position of Joint at Initial Contact (°)</td>
<td>Hip</td>
<td>141±8</td>
<td>5</td>
<td>132±14</td>
<td>11</td>
<td>127±2</td>
<td>2</td>
<td>141±16</td>
<td>11</td>
<td>136±15</td>
<td>11</td>
<td>134±9</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Knee</td>
<td>161±5</td>
<td>3</td>
<td>152±8</td>
<td>5</td>
<td>143±8</td>
<td>6</td>
<td>149±10</td>
<td>7</td>
<td>150±9</td>
<td>6</td>
<td>152±11</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Ankle</td>
<td>98±6</td>
<td>6</td>
<td>97±4</td>
<td>4</td>
<td>89±6</td>
<td>7</td>
<td>76±17</td>
<td>22</td>
<td>86±16</td>
<td>17</td>
<td>93±8</td>
<td>8</td>
</tr>
<tr>
<td>Range of Movement (°)</td>
<td>Hip</td>
<td>62±30</td>
<td>49</td>
<td>35±8</td>
<td>22</td>
<td>51±9</td>
<td>18</td>
<td>12±5</td>
<td>43</td>
<td>25±14</td>
<td>57</td>
<td>56±22</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>Knee</td>
<td>69±13</td>
<td>18</td>
<td>37±9</td>
<td>23</td>
<td>59±19</td>
<td>32</td>
<td>44±7</td>
<td>17</td>
<td>41±14</td>
<td>34</td>
<td>64±11</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Ankle</td>
<td>29±9</td>
<td>32</td>
<td>21±11</td>
<td>51</td>
<td>38±10</td>
<td>26</td>
<td>39±9</td>
<td>24</td>
<td>30±13</td>
<td>44</td>
<td>33±11</td>
<td>32</td>
</tr>
</tbody>
</table>
4.1.4 Range of Movement

The range of movement (Table 3) is largely varied between individuals across all joints, however the female gymnasts tend to express a larger range of movement across the ankle, knee and hip (33.3°, 64.1° and 56.2°) than either of their male counterparts (29.9°, 40.6° and 28.3°). All individuals and groups showed high amounts of variability across all joints (CV>10%).

4.1.5 Maximum Knee Valgus Angles

Maximum knee valgus angles during landing show relatively similar results for the female gymnasts (12.6° and 15.2°), however the male gymnasts demonstrate more disparate values of 24.4° and 10.4° (see Table 3).

4.2 Continuous Variables

Continuous flexion-extension joint kinematics for the hip, knee and ankle were constructed to illustrate the movement patterns throughout landing. A decrease in the curve characterises flexion of a joint, with an increase in the curve characterising extension. The root mean squared difference (RMSD) was calculated to determine the difference between males and females across continuous data.

Angle-angle diagrams were created to illustrate the mean group and individual coordination patterns of the ankle and knee and knee and hip. The aim was to compare the coordination patterns between male and females during landing, and to compare the intra-variability of individuals between trials. Finally vector coding was applied to quantify the position of the limbs over a relative amount of time.

4.2.1 Continuous Flexion-Extension Joint Kinematics

At initial contact (0%) the ankle angle is fairly similar between males (86.2°) and females (93.2°). During impact the female ankle joint flexes more suddenly than the male ankle, flexing 10.9° in the first 8% of movement, more than the male ankle which only flexes 3.7° in the same relative time. Following the first 95% of movement the female ankles extend until the curve plateaus near 90% of movement, however the male ankle still extends till 100% of movement time (see Figure 4).

At initial contact (0%) the knee angle is nearly identical between males (150.2°) and females (151.7°). However at impact again the female knee also flexes rapidly through
36.6° in the first 17% of movement, more than the males again who only flex 18.8° in the same relative time. After this both male and female knees extend until they plateau at approximately 95% of movement (see Figure 5).

Figure 4. The continuous mean ankle angle profiles for males (black line) and females (grey line) together with the standard deviations (dashed).

Figure 5. The continuous mean knee angle profiles for males (black line) and females (grey line) together with the standard deviations (dashed).
At initial contact (0%) the hip angle is also very similar between males (136.3°) and females (133.8°). At impact the female hip also flexes more than the males, flexing 16.9° in the first 21% of movement, more than the male gymnasts who only flex through 1.4° during the same relative time (see Figure 6).

The continuous angle profiles for the lower extremity joints all suggest the ankle, knee and hip to all subsequently flex after each other. The female gymnasts also make initial contact with the ground with a more extended position of the ankle and knee, however also create more flexion at all three joints.

The RMSD values calculated to represent overall difference between males and females revealed a 2.8%, 11.8% and 9.0% difference in ankle, knee and hip landing data respectively.
4.2.2 Angle-Angle Diagrams

Figure 7. Angle-angle plots of the ankle and knee angles during landing for females and males (A. F01, B. M01, C. F02 and D. M02). The bold line represents the mean coordination pattern with individual trials (fine lines) included to illustrate variability.
Figure 8. Angle-angle plots of the knee and hip angles during landing for females and males (A. F01, B. M01, C. F02 and D. M02). The bold line represents the mean coordination pattern for the both groups with individual trials (fine lines) included to illustrate variability.

The angle-angle diagrams illustrating coordination for the ankle and knee allows patterns of coordination to be compared. Intra-participant variability seems relatively similar, more so in the ankle and knee coordination profiles. It is also of interest to note the inter-sex variability which is somewhat apparent across individuals but less so within the specific groups.
4.2.2 Vector Coding

Figure 9. A time series profile of the resulting coupling angles (ankle and knee) for males (black line) and females (grey line).

The time series profiles of the ankle and knee exhibits similar coordination patterns for both males and females, however noting a slight delay for males during landing (Figure 9). Both profiles show knee extension prior to ankle plantar flexion followed by ankle dorsi flexion and subsequent knee flexion as one would expect. However the relative amount of time ankle and knee flexion occurred from initial contact till maximum flexion differs between males and females. The female gymnasts experience this 5% earlier in the movement time than males, possibly owing to differing coordination patterns and motor control. The time series profiles of the knee and hip however show more disparities between the coordination patterns exhibited by the male and female gymnasts (Figure 10).
Figure 10. A time series profile of the resulting coupling angles (knee and hip) for males (black line) and females (grey line).
CHAPTER 5
DISCUSSION
5.0 Discussion
The aim of the study was to compare the landing techniques between male and female artistic gymnasts following a back tuck dismount from the high bar. To meet this aim the individual kinematic variables presented by each gymnast were appraised, followed by an assessment of the intra and inter-variability of these variables. The primary intention was to establish any particular trends in landing technique performed by male and female gymnasts, to appreciate the influence, if any, of sex on the strategies chosen. The probability of injury as a consequence of these elected strategies was the main focus, where highlighting possibly injurious landing strategies of both male and female gymnasts could inform training, a possible rule change and reduce injury potential.

5.1 Findings from Kinematic Data

5.1.1 Sagittal Plane Kinematics
Sagittal plane kinematics of the lower extremities have been analysed in many studies with the intention of identifying potential injury variables during impact (McNitt-Gray, 1991; Chappell et al., 2002; Decker et al., 2003; Kernozek et al., 2005). At initial ground contact the female gymnasts generally showed greater extension of the ankle and knee, similar to the findings reported by Decker et al. (2003), however individual characteristics of the male gymnasts in particular influenced the group means. Gymnast M01 demonstrated extension values similar to gymnast F01, so the group means calculated for male and female gymnasts should be interpreted with some caution. Increased knee flexion at initial contact is reported to decrease the forces on impact (Devita and Skelly, 1992), however more recently Yu et al. (2006) suggested differently, highlighting the importance of active knee and hip flexion to reduce impact forces and not necessarily simply increased flexion at initial contact. Conversely landing with greater ankle plantar flexion at initial impact is suggested to enhance the attenuation of ground reaction forces (Self & Paine, 2001). The gymnasts selecting to land with greater knee and hip extension may be utilising the ankle plantar flexor musculature more to dissipate the forces on landing, favourable for protecting the knee joint up the kinetic chain (Decker et al., 2003; McClean et al., 2007). Substantial extension of the lower extremities at initial contact coupled with a reduction in energy absorption can prohibit the most beneficial muscle mechanics (Decker et al., 2003). This can often allow the quadriceps muscles to create a pull on the tibialis anterior occasioning larger forces on the ACL (Pandy & Shelburne, 1997).
It was also supposed that the female gymnasts utilise a greater ROM at the ankle and knee to absorb a greater amount of energy on landing (Decker et al., 2003; Kernozek et al., 2005). Gymnast M01 exhibited little ankle ROM and hence also displayed little knee and hip ROM. Fong et al. (2011) recognised reduced ankle ROM to reduce knee ROM, sequentially presenting larger ground reaction forces and greater knee valgus displacement. This may be a potential explanation for the increase in knee valgus displayed by gymnast M01 during landing, regardless of his sex. Irrespective of the angular position of the limbs at ground contact, Decker et al. (2003) speculated that by increasing the ROM may allow gymnasts to dissipate the impact forces over a larger range of joint movement, protecting the ACL.

In addition to larger ranges of motion the female gymnasts expressed larger maximum flexion angles of the knee and hip, contradictory to that of the majority of earlier research (Malinzak et al., 2001; Chappell et al., 2002). Prior research indicated female athletes in particular to land with a more erect posture on landing, favouring the production of larger quadriceps over hamstrings activation and consequently predisposing them to a greater risk of ACL injury (Malinzak et al., 2001). However in this current study the male gymnasts were found to display this type of posture. A potential explanation for this could be insufficient height gained during the dismount, leaving little time for the male gymnasts to spot the landing and alter the body to ensure a safe landing. Another possible explanation could be the type of athletes used in these earlier studies to execute the drop landings. Both Malinzak et al. (2001) and Chappell et al. (2002) observed the kinematic differences between male and female volleyball, basketball and soccer players. Male gymnasts may be landing in this more extended posture to comply with what is expected in the code of points and not taking into account the prospective effects of this on injury risk.

The continuous knee angle profile (Figure 5) and the vector coding profile of the ankle and knee (Figure 9) further indicate female gymnasts to land with a greater degree of flexion, however the time taken to reach this state occurs at a much faster rate than the males. This implies that female gymnasts decelerate faster but utilise greater flexion to dissipate the force whilst male gymnasts decelerate slower yet land with greater extension. This is suggested to be a strategy often adopted by female gymnasts, with increased knee flexion acceleration thought to be an injury prevention mechanism (Fagenbaum & Darling, 2003). However, fast knee deceleration combined with little knee flexion has been proposed to increase ground reaction forces and should be avoided (Decker et al., 2003).
The angular velocity of the hip and knee joint during initial landing has been found to increase proximal tibia anterior sheer force and vertical ground reaction forces respectively (Yu et al., 2006). There were varying results within the study with the two males experiencing larger hip angular velocities and F01 and M01 experiencing larger knee angular velocities. Barlow, Gardner & McCaw (2009) suggested larger peak angular velocities to strongly correlate with negative joint work. Shultz et al. (2010) further recognised that a decrease in negative work was associated with increased joint laxity in females. Thus an increase in hip angular velocity coupled with a decrease in knee angular velocity, and therefore a possible decrease in energy absorption could produce a harmful landing strategy. Furthermore an increase in proximal tibia anterior sheer force combined with an increase in joint laxity could augment the risk of ACL injury further.

Ultimately limited hip and knee flexion in the sagittal plane is believed to generate an increase in frontal knee motion. Restricting the degrees of hip and knee flexion during impact is understood to place more load on the passive structures in the frontal plane (Pollard, Sigward & Powers, 2010), promoting ACL susceptibility further.

### 5.1.2 Frontal Plane Kinematics

Russell et al. (2006) have previously proposed that sex differences in terms of landing kinematics, may be more evident in the frontal plane of motion, in particular knee valgus and varus motions. Hamill & Knutzen (2009) defined a knee abduction angle of more than 17° to be considered genu valgus. According to this definition only one participant (M01) exhibited knee valgus in flexion, disparate to that often reported in the literature (Russell et al., 2006). Female athletes have regularly been observed to land with larger amounts of knee abduction (Ford et al., 2003; Hewett et al., 2005) however this was associated more with M01 in this study. Greater knee abduction in female athletes has been suggested to be because of insufficient neuromuscular control (Hewett et al., 2004), hip extensor strength (Pollard, Sigward & Powers, 2010) and hamstring strength (Wild et al., 2013), and has further been associated with higher rates of ACL injury (Beaulieu & McClean, 2012). In terms of kinematics it is of value to consider the limited range of ankle motion (ROM) displayed by gymnast M01 associated with the excessive amounts of knee valgus. Decreased dorsi flexion ROM has been acknowledged to increase the amounts of knee valgus during squats (Bell et al., 2012) mostly due to a restrictive soleus and gastrocnemius (Bell et al., 2008; Bell et al., 2012). These factors prevent the adequate anterior movement of the knee and tibia, allowing the foot to overcompensate by pronating.
and consequently internally rotating the knee and hip with subsequent knee valgus (Bell et al., 2008). Although these events have been observed during a squat movement, the possibility of the same effect during a landing cannot be discounted.

The frontal knee kinematic findings of this study are conflicting with that of certain previous research (Hewett et al., 2005). No obvious sex difference was reported between groups, with all gymnasts landing with varying degrees of knee valgus. The lack of sex differences in drop landing movements has been associated with a too simplistic task (Cortes et al., 2007). However for this study the lack of sex differences is hypothesised to be due more to their levels of expertise in the task (Pollard et al., 2004). High levels of expertise in activities that create a high demand for landing, such as gymnastics, are suggested to play a significant role in landing patterns (Gittoes et al., 2012; Bruton, O'Dwyer & Adams, 2013). The participants involved in this research held between 9-12 years of experience in gymnastics, proposing the greater amount of training time has developed greater motor control within higher level gymnasts (Bruton, O'Dwyer & Adams, 2013). Expanding on work by Gittoes et al. (2012) has better allowed the levels of expertise to be compared to distinctive coordination patterns executed by each gymnast. The findings allude that the gymnasts with greater levels of competence may demonstrate less intra-variability between trials, however research should continue to explore this concept further.

5.2 Coordination of the Lower Extremities

The coordination patterns of each individual gymnast were presented to understand if there were any tendencies associated between male and female gymnasts. An interpretation of the angle-angle plots suggests each gymnast to demonstrate their own “signature” coordination pattern as the most appropriate method of completing the specific task, similar to that found by Irwin & Kerwin (2009). Interestingly the male and female gymnasts also showed somewhat similar coordination strategies within the groups, with the female gymnasts revealing a smaller range of coordination across the trials. The lack of intra-variability observed within female athletes during high speed, unanticipated cutting movements has been suggested to increase the incidences of ACL injuries in women. This has been thought to be due to repetitive overload on the same mechanical structures or a lack of adaptability to react to the changing environment (Pollard et al., 2005). This indicates an importance for a relative amount of variability within gymnasts to allow for enough flexibility within the human system to adapt to environmental perturbations (Pollard et al., 2005), often more apparent in more experienced athletes (Wilson et al., 2008).
Wilson et al. (2008) reported a “U” shape relationship between variability and levels of expertise in triple jumpers indicating more elite athletes to express more variability to adapt to the constraints placed upon them. More recently however Hiley, Zuevsky & Yeadon (2013) suggested more experienced gymnasts to show less variability during mechanically important aspects of giant circles on the high bar. These differences could be explained due to the skill demand and the nature of the activity. Triple jumpers may present more variability because of repeated impact loading, whereas gymnasts performing giant circles may be unable to execute this skill with much variability.

Nonetheless within this current study the results adhere to that of Hiley, Zuevsky & Yeadon (2013) supporting the idea that more experienced gymnasts demonstrate less variability during particular movements. It could be hypothesised that the more experienced gymnasts express lower degrees of coordination variability due to the mechanical importance of the landing. Moreover, leading elite gymnasts perform superiorly by executing skills in adherence to the code of points (FIG., 2013), assuming little scope for variability within gymnastics as a sport. Perhaps due to the nature of the sport and years of experience retained by the gymnasts, there leaves little other options for the landing mechanics adopted. The lack of variation is reasoned to be potentially harmful due to overload on the same mechanical structures (Pollard et al., 2005). However with landing performance and technique completely corresponding with success, disadvantageous and potentially detrimental outcomes could be interrelated with the scoring system currently used to grade skills in gymnastics. It ought to be noted that this is a preliminary hypothesis and additional research should be undertaken using a larger sample with a wider range of expertise to truly ascertain if this is the case in gymnastic performances.

5.3 Limitations and Future Recommendations

Owing to logistics and safety measures, the difficulty of accurately measuring impact force data meant that only kinematic data was able to be collected. This also connotes that only assumptions can be presented regarding the effect of kinematic landing patterns on force production or attenuation, based on relationships between these variables presented by previous research (Decker et al., 2003; Yu et al., 2006; McClean et al., 2007; Fong et al., 2011). Moreover due to the location, the gymnasts kinematics were only assessed unilaterally removing the possibility of evaluating asymmetry between limbs, as this has been recognised as an important factor contributing to ACL injury (Ford et al., 2003; Hewett et al., 2005). Asymmetry assessment may also indicate bilateral differences during
landing as a contributing factor to ACL injuries (Pappas & Carpes, 2012). Additionally the upward marker acceleration method used to define the instance of touchdown would need authenticating so that the true validity of the procedure could be determined. Future research should continue to study gymnasts in their habitual environment, however additional work involving the collection of force data should be used to quantify the effects of kinematics on kinetics.

The sample size for the current study was relatively small, however the rationale for this was to assess the kinematic differences between highly trained gymnasts in an ecologically valid environment to appreciate if there was any influence of biological sex differences at all. Including a considerable sample size could be argued to be a better representation of the overall population, however this study provides an opposing justification for this. If a substantial sample was used, one male gymnast in particular, recognised as being at a serious risk of injury, may have been generalised into the group and essentially lost. A single subject design allowed individual characteristics to be acknowledged and analysed, avoiding the concept of generalising populations to obtain an average individual (Sidman, 1960). To further develop this study a larger sample size with a larger number of trials could have been used, however still approaching the research from a single subject design. As a consequence of this, more comprehensive conclusions could be drawn to truly appreciate if the landing characteristics of male and female artistic gymnasts can be generalised. Furthermore this could provide implications to coaches and scientists in sport, as individual, elite gymnasts’ needs in particular cannot be ignored. A larger sample size however could be used in further studies to ascertain the effect of expertise on the variability of movement in order to facilitate more suitable training regimes.

In addition future work should consider levels of expertise and the effect on variability in gymnastics especially, where performance and technique correlate to success. This could be of value when aiming to establish a potential rule change regarding the assessment and scoring of performances to reduce the risk of injury.
6.0 Conclusion

The current study was primarily designed to compare the landing technique between male and female artistic gymnasts following a back tucked dismount from the high bar. It was found that all gymnasts revealed potentially harmful landing mechanics by presenting kinematic patterns that have been previously reported in the literature as harmful.

Previously recognised kinematic variables associated with increased ACL injury disposition such as: higher peak hip angular velocity (Yu et al., 2006), reduced ankle ROM and knee ROM (Fong et al., 2011), limited knee flexion (Pollard, Sigward & Powers, 2010), and consequential increased knee abduction (Chappell et al., 2002; Fong et al., 2011) were somewhat exhibited by each gymnast during landing. All kinematic variables identified, excluding higher peak hip angular velocity were all exhibited by M01, hypothetically classifying him as the most vulnerable to ACL injuries. It is postulated therefore that lower extremity injuries such as ACL tears are potentially more associated with individual landing strategies, independent of their sex.

Another kinematic analysis was used to facilitate a further understanding concerning that of male and female gymnasts’ landing patterns in terms of lower limb coordination and intra-limb variability. Although the male and female gymnasts presented relatively similar coordination strategies, each gymnast exhibited their own “signature” pattern to complete the task. Furthermore the gymnasts categorised as the most experienced of the group displayed less variability between trials, consistently applying overload to the same mechanical structures. This has been documented as an injurious approach, however is hypothesised to be an issue that cannot be changed in gymnastics if the primary objective is to be successful. In relation to gymnastic style landings, a successful landing is defined as limited hip and knee flexion with feet together on impact (FIG., 2013), which has been reported in various biomechanical literature as harmful. As a consequence to execute a successful landing during a gymnastic dismount, potentially unsafe landing styles have to be executed to conform to the code of points.

Recognising the kinematic strategies employed by gymnasts in an ecologically valid study may be valuable in informing possible rule changes. By addressing this issue in the gymnasts habitual environment provides greater insight into the implications of the traditional landing style desired in gymnastics. This could have a possible inference on removing the emphasis enforced upon gymnasts by the code of points to land complex skills with a landing technique already deemed harmful in various literature. Ultimately this
study has aimed to add a small contribution towards sex differences in gymnastic style landings. It suggests that gymnasts should be considered as individuals regardless of their respective sex. This could inform better personalised training programmes in terms of progressive practices and strength and conditioning exercises. The emphasis would be to encourage safer landing techniques during dismounts from the high bar, in addition to developing greater muscular strength of specific muscles, such as the hamstrings, in order to avoid the potential of ACL injury in particular.
REFERENCE LIST


APPENDICES
APPENDIX A

PARTICIPANT INFORMATION SHEET
Title of Project: Comparison of landing kinematics between experienced male and female artistic gymnasts following a back tuck dismount from the high bar.

Participant Information Sheet

Background

This research project is concerned with comparing different landing techniques from a back tuck dismount from the high bar, between male and female artistic gymnasts.

This is to see if different genders land with different technique and if so, what this means in terms of a biomechanical perspective. The two areas that are of interest are injury and performance. Therefore the landing data will be analysed to help:

(i) Identify incorrect technique to aid in the reduction of injury
(ii) Identify correct technique to help increase the quality of performance of that particular skill.

Your participation in the research project:

Why you have been asked

You have been invited to participate in this study because of your ability to perform the skills that are required. All participants will have the opportunity to see their own individual results and what this means for them.

What would happen if you agree to be a participant in this study

If you agree to partake in the study, there are 2 main things that will take place.

1. You will be required to wear tight clothing, such as a leotard or gym shorts to help reduce soft tissue motion and to re-create similar conditions that you are used to training and competing in. Joint centre markers will then be placed approximately on the foot and at the ankle, knee, hip and shoulder joint centres. These will be stuck on by double-sided tape and are used to collect the data.
2. You will be asked to attend an individual data collection trial where it will be asked of you to perform a tuck back dismount from the high bar and land onto a crash mat.

Are there any risks?

There are no significant risks by taking part in this study. Obviously there are risks with any gymnastics moves, however this is something you should feel comfortable with and used to doing. Crash mats shall also be placed all around the performing area, just in case, and a qualified gymnastics coach will be there to check the safety of the equipment and to spot the gymnast performing.
Your rights
Participating in this study does not mean that you give up any legal rights. In the very unlikely event that something does go wrong during data collection, Cardiff Metropolitan fully insures both staff and any participants involved. You are also free to drop out of the study at any time, and this will not be held against you or affect your status or grades at Cardiff Metropolitan University.

What happens to the results of the data collection?
The results of the data collection and analyses are collected and will be stored securely on a password protected computer at the Cardiff Metropolitan University. My Dissertation Supervisor and the Dissertation Coordinator will have access to the data collection and analysis files. The files will be coded so your digitised data is unidentifiable, however a record of which participant is which code will need to be kept so that any data analysis, you as a participant wish to see will be the correct one and available.

Are there any benefits from taking part?
Yes, by taking part you will have the opportunity to have your landing performance biomechanically analysed at no cost.

What happens next?
After reading this information sheet fully and understand it completely, you shall find a consent form to be completed if you agree to take part in this study. If there is anything you don’t understand or need clarification on, please ask myself (Rebecca Straker) or my dissertation supervisor (Dr Tim Exell), and we would be happy to answer this for you.

How we protect your privacy:
As has already been mentioned, every step will be taken to protect your privacy. All information about you will be stored on a password protected computer at the university away from the consent forms. At the end of the study all information gathered regarding you shall be destroyed. Only consent forms with your name shall be kept as this is a requirement set by Cardiff Metropolitan University.

Further information
If you have any queries regarding the research or the data collection and what you are expected to do, please feel free to contact us.

Miss Rebecca Straker
☎️  ♦️  ♣️  ♠️  st20021532@outlook.cardiffmet.ac.uk
APPENDIX B

INFORMED CONSENT
CMU PARTICIPANT CONSENT FORM

UREC Reference No:

Title of Project: Comparison of landing kinematics between male and female artistic gymnasts following a back tuck dismount from the high bar.

Name of Researcher: Miss Rebecca Straker

Participant to complete this section: Please initial each box.

1. I confirm that I have read and understand the information sheet dated .......... For this study, I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.  

2. I understand that my participation is voluntary and that it is possible to stop taking part at any time, without giving a reason.  

3. I also understand that if this happens, our relationships with Cardiff Metropolitan University, or our legal rights, will not be affected.  

4. I understand that information from the study may be used for reporting purposes, but that you will not be identified.  

5. I agree to take part in the study of back tuck dismounts from the high bar.

Name of Participant

Signature of Participant

Date

Name of person taking consent

Signature of person taking consent

Date
APPENDIX C

WINTER’S RESIDUAL ANALYSIS
Figure 11. Winter’s residual analysis for participant M01 (A), F01(B), M02(C) and F02 (D).
APPENDIX D

Figure 11. The classification of coordination based on vector coding and angle-angle analysis adapted from Chang et al. (2008).