LOWER-LIMB BIOMECHANICAL ASYMMETRY IN MAXIMAL
VELOCITY SPRINT RUNNING

by

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A thesis submitted for the degree of Doctor of Philosophy
University of Wales Institute, Cardiff
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ABSTRACT

LOWER-LIMB BIOMECHANICAL ASYMMETRY IN MAXIMAL VELOCITY SPRINT RUNNING

T. A. Exell, University of Wales Institute, Cardiff, 2010

Biomechanical asymmetry analyses have provided valuable insight into submaximal running and walking gait. Knowledge of asymmetry in sprint running is limited due to traditional unilateral methods of data collection. The overall aim of this research was to develop insight into kinematic and kinetic asymmetry in sprint running, with the purpose of informing future research specifically into maximal velocity sprint running.

Asymmetry was quantified for a group of trained sprint runners (mean velocity = 9.03 m·s⁻¹) using an existing symmetry angle (θ_SYM) measure. Biomechanical methods were developed to maximise the collection of kinematic data utilising both marker-based and non-intrusive techniques, and kinetic data using multiple force plates. Calculations were extended, to build on the θ_SYM, and used for quantifying overall kinematic and kinetic asymmetry for individual athletes. Novel asymmetry scores were developed that incorporated the previously negated consideration of intra-limb variability. The interaction of kinematic and kinetic asymmetry was compared for a range of sprint runners using the newly created asymmetry scores.

θ_SYM values were larger for key kinematic variables than step characteristics; values of 6.7% and 1.7% were reported for touchdown distance and step frequency, respectively. The largest asymmetry values were kinetic, with some θ_SYM values exceeding 90%. The magnitude of asymmetry and variables that displayed significant asymmetry varied on an inter-athlete basis. Kinematic and kinetic asymmetry scores developed within this research ranged from 4.5 to 27.6 and 6.3 to 28.7, respectively; however, no consistent relationship between kinematic and kinetic asymmetry was found. Compensatory kinetic mechanisms may serve to reduce the effects of asymmetry on step characteristics and the performance outcome of step velocity. The novel bilateral analyses performed in this research identified the presence of asymmetry, indicating that unilateral analyses of sprint running may lead to important information being overlooked.
PUBLICATIONS

Conference Articles:


Conference Presentations:

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My friends and family, particularly my parents, who have offered continued support and encouragement over the years. You are wonderful people and I am always grateful.

Finally, my girlfriend, Lisenka, for her endless love and support ‘baie dankie’.
DEDICATION

In memory of my grandfather, John H. Myatt
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<td>two-dimensional direct linear transformation</td>
</tr>
<tr>
<td>3D-DLT</td>
<td>three-dimensional direct linear transformation</td>
</tr>
<tr>
<td>ABSθ&lt;sub&gt;SYM&lt;/sub&gt;</td>
<td>absolute symmetry angle</td>
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<tr>
<td>ADF</td>
<td>absolute difference factor</td>
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<tr>
<td>ANOVA</td>
<td>analysis of variance</td>
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<td>BW</td>
<td>body weight</td>
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<td>body segment inertia parameters</td>
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<td>iliac&lt;sub&gt;MID&lt;/sub&gt;</td>
<td>mid-point of markers positioned on the left and right iliac crests</td>
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<td>IMP&lt;sub&gt;H&lt;/sub&gt;</td>
<td>net horizontal impulse in antero-posterior direction during contact</td>
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<tr>
<td>IMP&lt;sub&gt;V&lt;/sub&gt;</td>
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<td>KAS</td>
<td>kinetic asymmetry score</td>
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<tr>
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<td>mean support moment during contact</td>
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<td>metatarsal-phalangeal joint</td>
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<td>PB</td>
<td>personal best</td>
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<tr>
<td>R-L</td>
<td>step from touchdown of right foot to subsequent touchdown of left foot</td>
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<td>RDF</td>
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<tr>
<td>RMSD</td>
<td>root mean squared difference</td>
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SD  standard deviation
SF  step frequency
SI  symmetry index
SL  step length
SV  step velocity
TD  touchdown
TO  take off
WANET net ankle work during contact
WKNET net knee work during contact
WHNET net hip work during contact
x  medio-lateral direction
y  antero-posterior direction
yTD horizontal distance between toe and mass centre at the point of touchdown
z  vertical direction
zHMIN minimum height of mid-hip marker during contact phase
zKMAX maximum height of ‘swing leg’ during contact phase
%RMSD percent root mean squared difference
ΘHMAX-EXT maximum hip extension angle of ‘ground leg’ during contact
ΘKMIN-FLEX minimum knee flexion angle of ‘swing leg’ during contact phase
ΘSYM symmetry angle
CHAPTER 1 – INTRODUCTION

1.1 Overview

Sprint running is of global interest due to athletes performing at the body’s physical limits during a race. Beneke and Taylor (2010) described the 100 m sprint as the blue riband event in athletics competitions, due to the esteem associated with victory in the event along with the winner being awarded the title of the “...fastest human on earth” (Beneke & Taylor, 2010). During a period of 43 years (1964 to 2007) the 100 m world record was reduced from 10.06 to 9.74 s (www.olympic.org, accessed 20/08/2010). Since then, in a period of just two years, the current Olympic and World Champion has reduced this record to 9.58 s (www.iaaf.org, accessed 20/08/2010). The extraordinary ability of the current champion and the magnitude by which he broke the previous world record has led to a large amount of current public interest in sprint running and made the performance of this unique athlete a popular research topic (Beneke & Taylor, 2010; Eriksen et al., 2009; Helene & Yamashita, 2010). Whilst analysis of the world’s fastest sprint runner can enhance understanding of that individual’s performance; analysis of athletes ranging in ability can provide more information relating to sprint running in general and highlight similarities and differences that exist between athletes of different abilities.

Sprint running can be separated into a series of sequential step or stride cycles. A step cycle is defined as the period from the instant of touchdown (TD) of one foot to the subsequent TD of the contralateral foot. A stride comprises two successive steps and is therefore defined as the period from the instant of TD of one foot to the subsequent TD of the same foot. Hay (1994) noted that the objective of an athlete in a running race is to cover the distance of the race in the least possible time; therefore, performance in running can be directly linked to the athlete’s mean velocity throughout the race. Step velocity (SV) can be defined as the product of step length (SL) and step frequency (SF); where SL is the antero-posterior displacement of the feet from TD of one foot to the consecutive TD of the contralateral foot and SF is the inverse of step time, i.e. the number of step cycles that occur in one second. In maximum velocity sprinting, a negative interaction has been reported between the length and frequency of a step or stride (Hunter et al.,
The negative interaction that exists between step characteristics is due to maximum SV being achieved by optimising the relationship between SL and SF, with an increase in one factor resulting in a decrease in the other.

Step characteristics (SL & SF) are determined by the kinematic variables relating to the orientation and movement of the lower limbs, which are in turn controlled by the internal and external kinetics (Hay, 1994; Hunter et al., 2004a). Therefore, following an analysis of step characteristics, a study of the kinematic variables that control SL and SF is beneficial in explaining the step characteristic findings. Additionally, once the kinematic variables have been considered, an analysis of kinetic variables assists an increased understanding of the underpinning determinants of the movements. SL and SF tend to be reported as average values, but intra-athlete variation occurs in both throughout a run. Furthermore, there is often an implicit assumption that steps from each side of the body are similar.

The occurrence of asymmetry in walking and submaximal running has been the subject of much past research (Hamill et al., 1984; Vagenas & Hoshizaki, 1992; Zifchock et al., 2006). Asymmetry has been used in clinical gait settings to quantify inter-limb discrepancies and in running to highlight increased injury potential of one limb over the other. Despite the number of investigations focussing on asymmetry in submaximal running and walking gait, traditional unilateral methods of data collection have meant that asymmetry has not been investigated in sprint running. From a coaching perspective, knowledge of asymmetry may inform the nature of an athlete’s training based on performance differences between the two sides of the body. Information about asymmetry in sprint running also has implications for biomechanical research. Many biomechanical studies of sprint running have collected spatio-temporal data unilaterally due to constraints on data collection, such as the positioning of cameras or scanners (Bezodis et al., 2008; Gittoes & Wilson, 2010; Mann & Herman, 1985). In the event of a large amount of asymmetry being present for an athlete during sprint running, a unilateral analysis could provide an incomplete description of technique and important kinematic and kinetic factors could be overlooked if they occurred in the limb that was not chosen for analysis. It is important to collect accurate and appropriate data so that findings may enhance coaching knowledge through the coaching-biomechanics interface.
Therefore, the overall aim of this research was to develop insight into kinematic and kinetic asymmetry in sprint running, with the purpose of informing future research specifically into maximal velocity sprint running. This aim is addressed as a series of research questions focussing on the interaction of kinematic and kinetic asymmetry during sprint running.

1.2 Research Aims

To structure the research studies contained within this thesis, four main research aims were developed:

1) To gain an understanding of the asymmetry of step characteristics and associated kinematic variables for a range of sprint trained athletes.

2) To determine the underlying kinetic causes of the asymmetry observed in step characteristics and lower-limb kinematics on an individual athlete basis.

3) To develop a method of quantifying overall kinematic and kinetic asymmetry for individual athletes.

4) To quantify the influence of unilateral methods of data collection on biomechanical analyses of sprint running.

1.3 Development of Research Study Aims

In order to guide the analysis of data, discussion of results and formulation of philosophy, more specific research aims were devised for each study. The aims of each study were used to formulate specific research questions, detailed within Chapters 3 to 5.

Chapter 3 contained two studies; the first of which focussed on the development of methods to enhance the collection of kinematic data for the remaining studies in the thesis. Therefore, the first aim of Chapter 3 was:

**To develop methods for the collection of kinematic sprint running data that can be used during specific data collection sessions and, non-invasively, during athletes’ training or competition.**

Automated motion analysis systems are capable of collecting positional data of markers with high levels of accuracy, in the order of $5 \times 10^{-5}$ m (Richards,
A CODA motion analysis system was available for the collection of positional data. The CODA motion analysis system utilises active markers to calculate spatio-temporal data. Advantages of active marker based systems include the automated identification of markers and the absence of false marker tracking caused by light reflected by other objects located around the data collection volume, which is common with passive marker based systems. For the CODA system to be accepted as the favourable method of kinematic data collection for use in this thesis, the accuracy of the system required validation in the data collection environment and under the operation of the researcher.

Due to the intrusive nature of automated motion analysis systems and the need to attach markers to an athlete when collecting data via contemporary automatic systems, the use of such systems is limited in competition and training environments. Therefore, another less-obtrusive method of data collection was sought for the collection of competition and training data. 2D-DLT has been proven to allow accurate collection of planar data (Brewin & Kerwin, 2003; Irwin & Kerwin, 2001). The first study of Chapter 3 also addressed the accuracy of video data reconstructed via 2D-DLT compared to CODA for the calculation of kinematic data. The 3D reconstruction method of Abdel-Aziz and Karara (1971) was included in the comparison to allow non-intrusive collection of data within a calibrated 3D volume.

The final part of Study 1 investigated the calculation of horizontal sprint velocity without the need for a full-body marker set. A method was sought that would allow calculation of velocity when a full-body marker set is not suitable, such as when data are only available from one side of the athlete. Calculation of velocity based on markers located around the pelvis was also investigated as this would not be influenced by upper body movements when they are not of interest. Furthermore, the benefits of calculating centre of mass position (and hence velocity) using minimal sets of markers have been discussed by Forsell and Halvorsen (2009). These benefits included increased ecological validity and a reduction in the number of rejected trials due to markers being dislodged during data collection.
Following the development of suitable methods for the collection of kinematic data, the second study presented in Chapter 3 focussed on investigating the asymmetry of step characteristics. The second aim of Chapter 3 was:

**To assess the amount of asymmetry present in step characteristics of two highly trained sprint runners.**

Step characteristics have been identified as the highest order variables affecting sprint running performance (Hay, 1994; Hunter et al., 2004a). The initial asymmetry analysis of this thesis focussed on step characteristics to determine the extent of the asymmetry present in the variables that directly influence SV. Asymmetry found to exist in step characteristics would give indication that further asymmetries may be present in other kinematic and kinetic variables.

It has been reported in previous investigations into sprint running that a negative interaction exists between SL and SF (Hunter et al., 2004a; Kunz & Kaufmann, 1981). However, the interaction between the asymmetry present in each of the step characteristics has not been investigated. Due to the impact of SL and SF on SV and the negative interaction that exists between SL and SF, it was expected that asymmetry present in any of the variables will directly influence the asymmetry of the other two variables.

Following the findings of Chapter 3 regarding asymmetry of step characteristics, Chapter 4 focussed on asymmetry of kinematic variables that have been linked to success during sprint running. The aim of Chapter 4 was:

**To investigate asymmetry of the kinematics of the lower limbs during sprint running.**

Numerous biomechanical variables have been associated with successful technique in sprint running performance (Thompson et al., 2009). To allow comparison of kinematic asymmetry between athletes, an overall score of asymmetry was sought, which combined the asymmetry present in the kinematic variables of interest. Zifchock et al. (2008b) discussed the use of the symmetry angle (θ_{SYM}) for the quantification of asymmetry for biomechanical variables; however, the θ_{SYM} presented by Zifchock et al. (2008b) did not consider intra-limb variability in the quantification of asymmetry. Furthermore, a method was not
available that combined asymmetry of multiple variables in one score. Therefore, part of Chapter 4 centred on the development of a global kinematic asymmetry score (KMAS) that combined multiple variables associated with successful sprint running performance and which included intra-limb variability in the quantification of asymmetry. An overall score of kinematic asymmetry was sought so that it could be used to compare overall kinematic asymmetry between athletes.

Utilising the developed KMAS, the amount of asymmetry present in kinematic variables associated with successful sprint running was quantified for a group of sprint athletes. Due to the complex nature of the lower-limb actions during sprint running, numerous kinematic variables were included in the asymmetry score to provide information on kinematic asymmetry during the contact and flight phases. Kinematic variables were included in the asymmetry score based on their identification in biomechanical research and by expert sprint coaches as being important to successful sprint running.

The consistency of kinematic asymmetry was compared between athletes using the KMAS. Dufek et al. (1995) discussed the possible problems associated with group analyses due to inter-subject differences. Therefore, information about the inter-athlete differences in asymmetry was sought.

Restrictions when collecting data have led to some past studies having to collect unilateral data (e.g. Mann & Herman, 1985). Whilst there are situations when a bilateral approach is not possible, information about the differences in kinematic data between left and right sides was required. If results indicated that collection of data from one side can overlook important kinematic characteristics that are present in the contralateral limb, effort should be made to extend analysis to both limbs where possible. However, in the event of kinematic asymmetry being small in comparison to intra-limb variability, unilateral analysis would provide a suitable representation of the movements of both limbs.

In light of the findings relating to kinematic asymmetry reported in Chapter 4, a kinetic analysis of lower-limb asymmetry was undertaken in Chapter 5. An inverse dynamics analysis (IDA) was adopted to allow calculation of net joint power acting at the ankle, knee and hip joints of the lower limbs. Sadeghi et al. (2000)
recommended the use of joint power to measure kinetic asymmetry due to the inclusion of both joint moments and angular velocity. The aim of chapter 5 was: **To investigate the kinetic asymmetry of the lower limbs during sprint running, in light of the kinematic asymmetry reported in Chapter 4.**

An IDA was employed for the calculation of net joint moments and powers at the ankle, knee and hip joints. Ground reaction force data required as an input into the inverse dynamics calculations were collected via piezoelectric force plates. Force plates are relatively small in relation to an athlete’s SL; therefore, it is common for an athlete to miss the plate completely when one force plate is used, increasing the number of trials rejected from analysis (Bezodis et al., 2008; Johnson & Buckley, 2001). The addition of a second force plate can increase the area of data collection. However, when more than one force plate is used, the effect of foot contacts occurring across plate boundaries may lead to errors in the calculation of the point of force application. Therefore, prior to the collection of kinetic sprint data, a verification study was required to evaluate the method of collecting force and centre of pressure data from multiple force plates.

As with the kinematic analysis, a kinetic score of asymmetry was required, to allow comparison of kinetic asymmetry within a group of athletes. Having overall scores of kinematic and kinetic asymmetry for each athlete also allowed a comparison of the two for each athlete, providing information on any relationship between kinematic and kinetic asymmetry. Kinetic variables were selected for analysis based on their influence on the kinematic variables analysed in Chapter 4. Individual joint kinetics were calculated for the ankle, knee and hip joints during the contact phase of sprint running. Overall kinetic asymmetry was also quantified for each athlete using the newly developed kinetic asymmetry score (KAS).

Kinetic variables determine the kinematic responses associated with successful sprint running technique. A cause-and-effect relationship can be seen between many kinetic and kinematic variables analysed during sprint running. The interaction between kinetic and kinematic variables was investigated to determine whether it extended to lower-limb asymmetry. Other factors, such as strength imbalances (Vagenas & Hoshizaki, 1991), also influence asymmetry. Therefore, a link between kinetic and kinematic asymmetry was not a foregone conclusion and
asymmetry present in one of the two variables could have been due to a compensatory mechanism present within one limb to reduce the effect of a strength or technique imbalance (Sanderson & Martin, 1996).

Due to the additional equipment required for the collection of kinetic data, kinetic analyses tend to include fewer numbers of trials than kinematic analyses. The need for athletes to contact a force platform also leads to a higher number of trials being rejected for kinetic analysis (Bezodis et al., 2008; Johnson & Buckley, 2001). Due to the difficulties involved with kinetic data collection, a unilateral approach is often adopted. However, the effects of unilateral analysis on kinetic sprint running data are not yet known. If kinetic asymmetry is large compared to intra-limb kinetic variability, a unilateral approach to data collection could result in misleading kinetic results that are not representative of the unmeasured side of the body.

1.4 Organisation of Chapters

1.4.1 Chapter 2 – Review of Literature
Chapter 2 contains a review of literature relating to the aims of this thesis. Included in this chapter are reviews of research specifically on sprint running, analysing factors such as step characteristics, and kinematic and kinetic variables associated with sprint performance. Studies that have investigated asymmetry of submaximal running and walking were reviewed; due to the lack of research into asymmetry during sprint running. Finally, traditional and contemporary methodological approaches were considered, along with the benefits and weaknesses associated with each. The review of literature led to the development of research questions that guided the studies contained within Chapters 3 to 5.

1.4.2 Chapter 3 – Development of Methods for the Assessment of Step Characteristic Asymmetry in Maximal Velocity Sprint Running
Chapter 3 contains two studies; the first of which developed methodologies for the collection of spatio-temporal data throughout the remainder of the thesis. The second study provided an initial insight into potential asymmetry of sprint running through an analysis of step characteristics. Following the analysis of step characteristics, more detailed analyses were undertaken in Chapters 4 and 5 to explain and gain understanding of the established asymmetry.
1.4.3 Chapter 4 – Kinematic Asymmetry of Maximal Velocity Phase Sprint Running
An analysis of kinematic asymmetry is contained within Chapter 4. This study was performed to explore the causes of asymmetry reported in step characteristics in Chapter 3. The study included 10 athletes of ranging ability, who were analysed on an individual basis. A prominent section of the chapter was the development of a global score of kinematic asymmetry, encompassing numerous kinematic measures associated with successful sprint running and incorporating intra-limb variability. The KMAS was then utilised to compare kinematic asymmetry between athletes.

1.4.4 Chapter 5 – Kinetic Asymmetry of the Stance Phase in Maximal Velocity Sprint Running
Chapter 5 contains a methodological section to verify the accuracy of collecting centre of pressure data from two force plates, which increased the kinetic data collection area and increased the number of trials that could be collected. The verification of such a method was required before kinetic data could be collected for the analysis of asymmetry. An IDA was utilised in Chapter 5 to address questions on kinetic asymmetry during sprint running. Eight athletes were included in this study with the kinetic data used to both provide a kinetic score of asymmetry for each athlete and also to explain the kinematic asymmetry reported in Chapter 4.

1.4.5 Chapter 6 – General Discussion
Chapter 6 includes a discussion of the major findings of the research, along with an appraisal of methods used and demonstration of the insight that has been gained. The research aims established in Chapter 1 are addressed and implications of the asymmetry results are discussed from coaching-biomechanics and data collection perspectives. Limitations of the research are outlined, before potential directions for future research are presented.
CHAPTER 2 – REVIEW OF LITERATURE

2.1 Introduction

It is the aim of an athlete during a sprint race to cover the race distance in the shortest possible time. This is achieved by maximising their horizontal velocity. How maximum velocity is accomplished has been the subject of many previous biomechanical studies, which will form a major section of this literature review. Since step velocity (SV) is the product of step length (SL) and step frequency (SF) (Mero & Komi, 1994), the initial focus will be on the interaction of these three elements. Following step characteristics, the next focus is on the kinematic variables affecting SL and SF, followed by the kinetic variables that govern the kinematics. A review of asymmetry and variability studies follows the initial performance section, with the final section of the chapter considering data collection methods for the analysis of sprint running.

2.2 Biomechanics of Sprint Running

2.2.1 Performance and Injury Perspectives

The purpose of most biomechanical investigations into sprint running is to enhance understanding of either performance related factors (Bezodis et al., 2008; Luhtanen & Komi, 1978; Mero & Komi, 1985) or causes of injury (Chumanov et al., 2007; Kameyama et al., 1994; Yeung et al., 2009). Performance and injury studies may both provide beneficial information for coaches, as knowledge of limits to performance is beneficial when attempting to enhance maximal performance but any injury can severely inhibit an athlete’s physical preparation and development. However it is not until recently that attempts have been made to develop the coaching-biomechanics interface (Kerwin & Irwin, 2008) and bridge the gap between sprint running biomechanics research and coaching knowledge (Thompson et al., 2009).

2.2.2 Phases of Sprint Running

It has been suggested that sprint running can be separated into three distinct phases for analysis. These phases are termed the acceleration phase, the maximum velocity phase and the speed endurance phase (Delecluse et al., 1995;
Volkov & Lapin, 1979). The start or block phase has also been analysed as a separate phase by some authors (Mero et al., 1992).

The relative duration of each phase varies for different athletes and appears to be linked to the performance level of the athlete. Ae et al. (1992) reported that, for the elite athletes investigated, maximum velocity was not achieved by some until the 70 to 80 m section of a 100 m sprint. Conversely, Mero et al. (1992) found that in non-sprinters, maximum velocity was achieved much sooner. Helene and Yamashita (2010) reported that the current World and Olympic champion and world record holder reached maximum velocity at ~60 m into the 100 m race.

The maximal velocity phase is of interest to coaches and researchers, due to the athlete performing at their physical limit during this phase. Mann and Sprague (1980) noted that the maximal velocity phase is of interest due to the high force characteristics associated with the phase. The high forces experienced by sprint runners during maximal velocity sprinting have also been associated with the high occurrence of hamstring injuries (Yeung et al., 2009) within the event.

2.2.3 Summary
Biomechanical analyses of sprint running have investigated the physical demands associated with different phases of a sprint race. The maximal velocity phase is of interest due to athletes performing at their physical limits. Traditional research has focussed on performance and injury perspectives with analyses grounded using scientific theory. Some contemporary studies have focussed on bridging the gap between biomechanics and coaching knowledge, using coaches’ expertise to inform biomechanical analyses.

2.3 Performance Determinants of Sprint Running
2.3.1 Step Characteristics
Sprint running velocity is well published as being the product of SL and SF (Hay, 1994; Hunter et al., 2004a; Luhtanen & Komi, 1978). Maximum sprint velocity occurs when both these factors are maximised. However, it is well documented that a negative interaction exists between the two factors (Donati, 1995; Hunter et al., 2004a; Kunz & Kaufmann, 1981), due to the conflicting demands associated
with the increase of each. It is clear therefore, that to achieve maximum sprint velocity, the optimum combination of SL and SF must be achieved. Despite the wealth of published research on the subject of the interaction between SL and SF, there are many conflicting views between different studies, in some cases by the same authors (Mero & Komi, 1985; 1986), as to which factor is most influential on running velocity. Studies that have investigated changes in SL and SF relative to SV can be grouped into two categories; intra-subject studies that have compared step characteristic values for the same athletes running at different velocities and inter-subject studies that have compared athletes of different ability when performing maximally.

**Intra-Athlete Studies**

In a study by Luhtanen and Komi (1978), six national level athletes were analysed (mean maximum velocity 9.30 m·s⁻¹). Data were collected from multiple runs, where athletes were instructed to run at 40, 60, 80 and 100% of their maximum velocity (although mean velocity values actually equated to efforts of 42, 69, 86 and 100%). Results showed a nonlinear increase in SL and SF, with initial increases in velocity being due to increased SL, but approaching maximum velocity, SL plateaued and further velocity increases were the result of increases in SF (Fig. 2.1).

![Figure 2.1. Relationship between SL, SF and velocity (adapted from Luhtanen & Komi, 1978).](attachment:image.png)
Mero and Komi (1985) compared 22 sprinters (13 males and 9 females) running at submaximal (8.47 m·s⁻¹), maximal (9.25 m·s⁻¹) and supramaximal (10.04 m·s⁻¹) velocity. To reach supramaximal velocity, athletes were towed by an assistant runner via a rubber rope. The results of the study of Mero and Komi (1985) showed that changes from maximal to supramaximal velocity (mean increase of 8.5%) were primarily due to increases in SL (0.14 m) rather than SF (0.07 Hz). This finding is not surprising as the ‘drawing’ system applied a constant horizontal force (30 to 45 N) on the athletes; therefore, they were being horizontally accelerated during the flight phase of every step, which would result in an increased SL for a ‘supramaximal step’ over an otherwise identical step during a maximal trial due to the acceleration applied during the flight phase. Conversely, when comparing maximal with submaximal trials, (which coincidently also had a mean difference in velocity of 8.5% compared to maximal runs) the increased velocity of the maximal trials were due to an overwhelming increase in SF (4.02 to 4.49 Hz) compared to a minor decrease in SL (2.10 to 2.06 m). The step characteristic changes from submaximal to maximal velocity reinforce the theory of Luhtanen and Komi (1978) that, approaching maximum velocity, increases in velocity are due to increases in SF.

In a subsequent study, Mero and Komi (1986) implemented a methodology combining aspects of the previous studies of Luhtanen and Komi (1978) and Mero and Komi (1985) with data collected from 19 athletes running at velocities ranging from 50 to 110% of their maximum. Supramaximal velocity was reached via a towing system as in the previous study (Mero & Komi, 1985). The causes of increased velocity from submaximal to maximal were similar to those reported in the previous studies (Luhtanen & Komi, 1978; Mero & Komi, 1985) with initial increases in velocity being largely due to increased SL, which began to level off as maximum velocity was approached and further velocity gains mostly accounted for by increases in SF (Fig. 2.2). In contrast to the results of Mero and Komi’s (1985) earlier study on supramaximal running, increases in velocity from maximal to supramaximal were accounted for by a 6.9% increase in SF with SL only increasing by 1.5%. However, in this study athletes were instructed to “…press the leg as fast as possible onto the ground to increase stride rate…” (Mero & Komi, 1986). Given that it was a conscious aim of the athletes to increase SF, it seems that they were able to achieve this by ‘trading off’ SL for an increased SF, although
SL still exhibited a slight increase, possibly due to the horizontal acceleration effects of the towing system as mentioned previously. The contrast between the results of Mero and Komi’s (1985; 1986) studies on supramaximal velocity running highlight that caution should be taken when interpreting the results of supramaximal velocity studies as it appears that athletes may be able to consciously select whether to increase SL or SF to generate an increase in running velocity.

![Graph showing the relationship between SL, SF, and SV for more-skilled male (MA), less-skilled male (MB), and female (W) athletes.](image)

Figure 2.2. Relationship between SL, SF and SV for more-skilled male (MA), less-skilled male (MB) and female (W) athletes (adapted from Mero & Komi, 1986).

Nilsson and Thorstensson (1987) studied the adaptability of SL and SF when walking and running at different velocities ranging from 1 to 8 m·s\(^{-1}\). They found that each of the eight athletes studied subconsciously selected their own natural combination of SL and SF for each velocity, but that each velocity could also be achieved with both a higher and lower SF through conscious effort. The results of this study reinforce the fact that the same running velocity can be achieved via different combinations of SL and SF and that, at submaximal velocities, this can be the case in the same athlete. However, this investigation did not study step characteristics at maximum velocity, which may prove to be less adaptable as the athlete is working at their limits of performance.
Donati (1995) also recognised that different ratios of SL and SF could achieve the same velocity, but theorised that there is one specific ratio for each athlete that will produce their maximum velocity. Donati (1995) depicted this graphically (Fig. 2.3) by plotting athletes’ velocities for a number of maximum effort sprint runs against the number of steps taken for each run. The resulting graph shows that if either SL or SF is too high, velocity will be reduced and that maximum velocity (for that specific athlete) can be calculated as the point at which the two lines intersect. Donati (1995) noted that for the skilled athletes that he investigated, the athletes naturally selected ratios of SL and SF that were very close to the optimal ratios calculated graphically.

![Figure 2.3. Relationship between SL and SF and velocity (adapted from Donati, 1995).](image)

Weyand et al. (2000) compared 33 male and female athletes running on a treadmill at velocities from ~2.5 m·s^{-1} up to their maximum (ranging from 6.2 to 11.1 m·s^{-1}). They noted that increases in horizontal velocity were due to SL increases at lower velocities and then SF as athletes approached their maximum velocity. The finding of Weyand et al. (2000) suggests that increases in maximal velocity performance may be achieved through increased SF, reinforcing the findings of Luhtanen and Komi (1978) and Mero and Komi (1986).
In a later study, Kuitunen et al. (2002) compared ten trained sprinters running at a range of velocities relating to 70, 80, 90 and 100% of their maximum. The authors reported that, as in previous studies (Luhtanen & Komi, 1978; Mero & Komi, 1985; 1986; Weyand et al., 2000), increases in running velocity from submaximal to maximal were almost entirely due to increases in SF (3.30 to 4.50 Hz) rather than SL (2.12 to 2.16 m).

In a study from his doctoral thesis, Bezodis (2006) investigated how seven sprinters’ SL and SF values changed with velocity over a period of six months. Results of the study showed that, for five out of the seven sprinters tested, increases in velocity were very closely linked to increases in SF. Of the other two sprinters tested, one displayed a tendency for velocity to increase with increased SL, whilst the final sprinter showed no clear relationship with either SL or SF and velocity. Bezodis (2006) noted, however, that at the time of testing the two sprinters that did not exhibit relationships between velocity and SF had recently recovered from injury, which may have affected technique.

Studies that have employed an intra-athlete approach to investigate step characteristics seem to be in agreement that changes in velocity from submaximal to maximal are largely due to increases in SF. However comparing between submaximal and maximal velocity running may not offer an explanation as to which factor limits performance, due to athletes being able to select different combinations of SL and SF to achieve the same running velocity as presented by Donati (1995). Conversely, the comparison of maximal and supramaximal sprint running may give false indication of potential increases in SL or SF due to the constant horizontal force that is applied to the athlete. Therefore, inter-athlete studies have also been performed to allow comparison between athletes of different ability when performing maximally.

**Inter-Athlete Studies**

Kunz and Kaufmann (1981) studied the biomechanical variability between 16 male decathletes and three elite sprinters running a 100 m race. Data were collected during national and international competitions, therefore maximal effort can be assumed. Although explicit values were not reported, graphs comparing SL and step time (the inverse of SF) with 100 m time indicated a stronger link between
velocity and SL than step time. Kunz and Kaufmann (1981) stated that there is no definite answer to the question of which factor is most important, but that there is an optimal balance for each athlete and that world class sprinters are better at achieving this balance. The idea of an optimal combination of SL and SF for each athlete was similar to that presented by Donati (1995), as discussed in the previous section on intra-athlete studies.

Mero et al. (1981) compared three groups of athletes with group mean maximum velocities of 9.75, 9.44 and 9.11 m·s\(^{-1}\). They reported that SL varied by just 0.04 m between the groups and that changes in velocity were largely due to changes in SF ranging from 4.17 Hz for the slowest group to 4.51 Hz for the fastest. They suggested that the ability to produce a higher SF is determined by the percentage of fast-twitch muscle fibres that an athlete possesses.

Following the earlier work of Kunz and Kaufmann (1981) and Mero et al. (1981), Mann and Herman (1985) analysed the 200 m sprint final of the 1984 Olympic Games. They collected data from higher and lower placed sprinters in the race (first, second and eighth place finishers) during both the non-fatigued (125 m) and fatigued (180 m) phases. Results showed that for both non-fatigued and fatigued phases, SL was 0.07 to 0.11 m larger for the gold and silver medallists than the eighth placed finisher. However, SL was almost identical for the first and second placed finishers during both phases, with no detectable difference during the non-fatigued stage and just 0.01 m difference at the fatigued stage. Conversely, SF was consistently higher for the first placed finisher than the other two sprinters, and was also higher for the second placed finisher than the eighth placed finisher during the non-fatigued phase. There was no detectable difference in SF between the second and eighth placed finishers during the fatigued phase of the race. They also noted that the gold medallist’s higher SF was accounted for by a shorter support time (0.10 s), the implication of which will be discussed in the subsequent kinematic section. The results presented by Mann and Herman (1985) support the finding of Kunz and Kaufmann (1981) that each athlete has an optimal combination of SL and SF, which can lead to inter-athlete differences in step characteristics for two athletes running at similar velocities.
Ae et al. (1992) analysed the eight finalists from the 100 m at the 1991 World Athletics Championships. Six of the athletes completed the race in a time of less than 10 s. The authors calculated mean SV, SL and SF values for each athlete for every 10 m interval of the race. One finding reported by Ae et al. (1992) was that the first placed finisher of the race had a shorter mean SL (2.37 m compared with 2.41 m) and higher mean SF (4.51 Hz as opposed to 4.40 Hz) than the second placed finisher, although this was not the case for every 10 m interval.

Gajer et al. (1999) investigated data collected from the semi-finals and final of the 1996 French National Championships. They grouped the six fastest athletes (mean time 10.18 s) and the six slowest athletes (mean time 10.52 s) and calculated mean SV, SL and SF for each 10 m interval, as in the study by Ae et al. (1992). Contrary to the work of Ae et al. (1992), Gajer et al. (1999) found that for every 10 m interval, the faster group displayed greater SL and lower SF than the slower group. Following this discovery, Gajer et al. (1999) re-investigated the work of Ae et al. (1992), comparing the four fastest finishers (mean time 9.89 s) with the four slowest finishers (mean time 10.04 s). When the data was grouped in this way, a similar trend to that of the original data of Gajer et al. (1999) was found in that, for nine out of the ten intervals, mean SL was greater for the faster group and that in seven of the ten intervals, mean SF was lower for the faster group. Furthermore, Bezodis (2006) noted that if the groups are altered so that the six fastest athletes are grouped together (with race times ranging from 9.86 to 9.96 s) and the two slowest are grouped together (with race times of 10.12 & 10.14 s), the findings are reversed and SF is then higher in the faster group and SL is higher in the slower group. Bezodis (2006) highlighted that the fifth and sixth placed finishers displayed shorter SL and higher SF than the other athletes, therefore their data affected the group that they were included in. The large variation of SL and SF values for the group provides further support of the theory presented by Kunz and Kaufman (1981) that each athlete has a specific optimal combination of SL and SF. The inter-athlete differences reported in these studies advocate the importance of a single-subject approach to sprint running data analysis (Dufek et al., 1995)

Weyand et al. (2000) also analysed the data discussed in the previous section on intra-athlete studies on an inter-athlete basis, they found that faster runners
displayed significantly greater SL than slower runners. An example of this was the fastest runner (11.1 m·s$^{-1}$) having a SL 1.69 times greater than the slowest runner (6.2 m·s$^{-1}$). When considering SF they noted a significant increase in SF with running velocity, although the increase was less than that reported for SL, with 1.16 times difference between the lowest and highest SF.

Hunter et al. (2004a) noted that there was inconsistency in the results of previous research as to which was the most important factor out of SL and SF. They calculated SL and SF for 28 male athletes (mean velocity ranging from 7.44 to 8.80 m·s$^{-1}$) and illustrated how the analysis used in a study of SL and SF can affect the finding. When they compared their results on an inter-athlete basis, they found that SL was the most important factor determining velocity. However, when they analysed their results on an intra-athlete basis the opposite was found, with SF having the greatest effect on velocity. Hunter et al. (2004a) suggested that developments in SL take a longer time, compared to relatively short-term developments in SF. One reason for SF being associated with short-term developments could be the increased muscle strength required to increase SL, which takes time to develop. Hunter et al. (2004a) also noted the clear negative interaction between the two factors and emphasised the need for sprint coaches to have a clear understanding of this so that a trained increase in one factor doesn’t lead to a reduction in velocity due to a greater decrease in the other factor. The potential for an increase in SL or SF to lead to a larger decrease in the other variable was also discussed by Hay (1994). The negative interaction observed between SL and SF can be explained mechanically. An increase in SL requires take off (TO) velocity to be increased, which can be achieved with a larger contact time (CT), therefore increasing step time, which is the inverse of SF.

Bushnell and Hunter (2007) compared trained sprinters with distance runners and non-runners during maximal velocity sprinting. They noted that during the finishing kick of a distance race maximising speed becomes the focus, rather than running economy, therefore recognising that it may be beneficial for distance runners to undertake sprint training. When comparing mean SL values (averaged over a complete stride), SV and SF calculated from the other two factors, the sprinters achieved a much higher mean velocity of 9.35 m·s$^{-1}$, compared with 8.40 and 8.26 m·s$^{-1}$ for the distance runners and non-runners, respectively. The higher velocity
was almost entirely achieved with larger SL as opposed to SF, with SL values of 2.23, 2.02 and 1.93 m and SF values of 4.19, 4.16 and 4.28 Hz for the sprinters, distance runners and non-runners, respectively.

2.3.2 Contact and Flight Phases
Each step cycle consists of a contact phase, when the athlete is in contact with the track surface, and a flight phase, when the athlete is not in contact with the track. Luhtanen and Komi (1978) investigated the interaction between the contact and flight phases of running steps. The authors found that CT was greater than flight time (FT) at the lowest velocity examined (3.90 m·s⁻¹), but that FT was greater than CT for all other velocities. There was a consistent reduction in CT as velocity increased. The authors divided CT into positive and negative sections; these were defined from the athlete’s vertical centre of mass (CM) position with the time from contact to the lowest point of the athlete’s CM being negative and the remaining time being positive. The ratio of negative to positive CT remained fairly constant, with negative CT forming approximately 35% of total CT.

Kunz and Kaufmann (1981) reported CT for elite sprinters of approximately 0.07 to 0.08 s compared with approximately 0.08 to 0.12 s for decathletes. SL was also larger for elite sprinters, indicating that they are able to produce more propulsive force during a shorter period of time.

Mero and Komi (1985) reported contact and flight times of 0.102 and 0.121 s, respectively for maximal sprints, which changed to 0.096 and 0.125 s during supramaximal sprints. An explanation for the changes in contact and flight times observed was not offered by the authors, although it is conceivable that, due to the constant horizontal accelerative force being applied to the athletes, they were able to make a trade off and apply greater vertical and less horizontal force than usual, resulting in increased FT.

In Mann and Herman’s (1985) comparison of the 200 m sprint, they reported contact and flight times of 0.10 and 0.13 s, 0.11 and 0.13 s and 0.125 and 0.12 s for the first, second and eighth placed finishers, respectively. Whilst these values only offer snapshots of one race, it suggests that elite sprinters may be separated by their ability to produce greater flight times with lower contact times.
Bushnell and Hunter (2007) compared CT in their study, which was discussed in the previous section on inter-athlete studies. The results of Bushnell and Hunter (2007) reinforced the findings of Luhtanen and Komi (1978) and Mann and Herman (1985); showing that CT reduced with increased velocity, with the sprinters having a mean CT of 0.109 s compared with 0.124 and 0.131 s for the distance runners and non-runners, respectively.

Ciacci et al. (2010) investigated the contact phase during maximal velocity sprint running, focusing on different methods used to define the braking and propulsive phases during ground contact. They reported a mean contact time duration of 0.104±0.007 s for a group of seven male sprint athletes. Ciacci et al. (2010) compared three methods of defining the point of transition between braking and propulsion using kinematic data, these were: 1) the instant of minimum vertical position of the CM, 2) the instant of maximum knee flexion, 3) the instant at which CM horizontal acceleration became positive. Mean results for the percentage of contact time that the transition between braking and propulsion occurred were 31, 45 and 57% for methods 1, 2 and 3, respectively.

2.3.3 Summary
From the results reported in the above section it is clear that, whilst there are certain recurring themes, there is no overall consensus on which factor of SL and SF most affects velocity. It appears that in studies comparing multiple athletes performing maximally, SL seems to be more closely related to velocity than SF, but for intra-athlete studies approaching maximum velocity changes in SF seem to have a greater effect on velocity. Studies that have examined contact and flight times seem to agree that increased SV is a product of reduced CT, which leads to a higher SF, and an increased FT, leading to increased SL.

2.4 Technique Contributors to Sprint Running

2.4.1 Kinematic Variables

*Whole Body analyses*
Sprint success is dependent on horizontal velocity, which is the product of SL and SF. To understand how larger SL and SF values can be achieved, one must consider the factors that directly influence them. Since the location and orientation
of body segments throughout a race determine SL and SF, the next level of analysis involves the consideration of the geometry of the performer. As mentioned previously, there is some disparity in the literature as to whether SL or SF has a greater effect on performance. As SL and SF are both products of many interlinked kinematic variables, it is likely that there will be similar discrepancies regarding the importance of many other kinematic measures.

Luhtanen and Komi (1978) reported that, in addition to their findings on SL and SF, there was an inverse relationship between vertical motion of athlete’s CM and horizontal velocity, with vertical CM motion decreasing as horizontal running velocity increased. The reduced vertical motion during increased running velocity reported by Luhtanen and Komi (1978) is reflected in the associated reduction in flight time discussed in Section 2.3.2.

Kunz and Kaufmann (1981) theorised that elite sprinters have their CM closer to their contact foot in the horizontal direction at the point of TD; if this is the case, it could reduce the effects of braking during contact, although the results presented by the authors illustrating this finding were not conclusive. Kunz and Kaufmann (1981) showed that elite sprinters exhibited a greater ‘forward trunk lean’ at TD then the slower decathletes; related to this they also reported a larger posterior trunk-thigh angle at TO. However, it is unclear whether this value was due to greater forward lean or an earlier termination of the propulsive part of contact.

Mann and Herman (1985) considered upper and lower body kinematics. They found that arm action did not influence sprint performance, suggesting that it is a mechanism to enhance balance. Therefore, sprinting success was attributed to the contributions of the lower limbs; namely angular velocity of the thigh during contact and the shank at TD. The authors suggested that increasing these angular velocities would reduce effects of braking at TD. In support of Kunz and Kaufmann (1981), Mann and Herman (1985) found that the first placed finisher consistently produced a smaller horizontal distance (0.25 m) between the foot and body at TD than the second (0.29 m) and eighth (0.32 m) placed finishers. The study highlighted leg angular velocity (the angle between the horizontal and a line joining the stance ankle and CM) during contact as another area where the medallists performed better, increasing leg angular velocity from contact to the drive phase.
by ~200 °·s⁻¹ compared with ~100 °·s⁻¹ for the 8th placed finisher. An eminent limitation of Mann and Herman’s (1985) study is the sample size. The data were collected during the final of the Olympic Games, allowing a rare chance to analyse sprint runners when performing at their absolute maximum due to periodised training cycles (Kirksey & Stone, 1998). However, limitations associated with the collection of data from the Olympic Games meant that only one step was available for both the maximal velocity and fatigue phases and for only three athletes.

Mann and Herman’s (1985) suggestion that the role of the upper limbs during running was to maintain balance, was investigated further by Hinrichs et al. (1987). In their study, Hinrichs et al. (1987) examined the function of the upper limbs during submaximal running ranging from 3.8 to 5.4 m·s⁻¹ and found that the arms did not contribute to the development of horizontal velocity. Hinrichs et al. (1987) noted that the arms did play a role in reducing changes in horizontal velocity and reducing lateral motion. The reduced lateral motion reported by Hinrichs et al. (1987) substantiated the theory suggested by Mann and Herman (1985) that the arms acted as a mechanism to maintain balance during running.

Hunter et al. (2004a) adapted Hay’s (1994) hierarchical model of sprinting to demonstrate the variables associated with successful sprint performance (Fig. 2.4). They used linear regression to investigate which factors were most influential on SL and SF and hence, SV. Based on their models, Hunter et al. (2004a) separated the determinants into four subcategories; stance time, stance distance, flight time and flight distance. They reported that the most influential variables for stance time and stance distance were mean horizontal velocity during stance, leg angle at TD, leg angle at TO and leg length. For flight time, height of CM at TO and vertical velocity of CM at TO were listed as the most influential, these two variables were also, along with horizontal velocity of CM at TO, the predictor variables for flight distance. Hunter et al. (2004a) discussed the negative interaction that they saw between SL and SF in two groups of athletes within their study; however, the athletes were grouped based on similarities in sprint velocity and leg length and notable differences in SF. Therefore, the reported finding that for similar velocities, athletes with larger SL had lower SF was, to some extent, a self-fulfilling prophecy. The authors construed that vertical velocity is the variable that causes the evident negative interaction between SL and SF, as greater
vertical velocity at TO leads to increased SL due to increased flight time, but decreased SF due to the larger duration of the step cycle.

Figure 2.4. Biomechanical determinants of SF (a) and SL (b) (Hunter et al., 2004a).
Many of the studies featured in this review have undertaken an experimental approach to determine the kinematic variables that have the greatest influence on sprint performance. However, Thompson et al. (2009) conducted interviews to gain understanding of what expert sprint coaches associated with good sprint running technique. Four high-order constructs were identified by the coaches as being highly influential to good sprint running technique; these were posture, hip position, ground contact and arm action. The authors went on to determine what the coaches specifically looked for when using these four terms. Posture was mainly related to core strength of the trunk, with coaches noting that the trunk should be strong to maintain a stable position during sprinting. Hip position was largely associated with the vertical position of the hips during sprinting, with an optimal position allowing full range of motion of the lower limbs. Three main ideas were associated with ground contact; firstly, minimising the distance between the lead foot and the athlete’s CM (yTD), secondly, maximising force production whilst simultaneously minimising CT and finally, the use of hip extension and knee flexion to drive the foot backwards during ground contact. Arm action was identified by the coaches as improving stability and balance during sprinting, reinforcing the notions of Mann and Herman (1985) and Hinrichs et al. (1987). However, the coaches claimed that arm action plays a vital role in sprint running technique, a finding that has not been replicated in biomechanical research. Thompson et al. (2009) noted that, for variables associated with ground contact (in particular yTD and CT), there was agreement between the coaches and previous biomechanical literature (Mann, 1985; Mero et al., 1992) as to their important influence on sprint performance.

The opinions of the coaches presented by Thompson et al. (2009) demonstrated that there are some variables (e.g. yTD) that have been advocated as being important to sprint running through both coaching knowledge and biomechanics research (Hunter et al., 2004a). Conversely, some variables (e.g. arm action, Thompson et al., 2009) have been identified by coaches as influential, without related scientific backing through biomechanics research; whilst other variables (e.g. knee flexion during swing, Hay, 1994) have been identified as important to sprint running through scientific theory without recognition by coaches. The lack of a consensus between coaches and biomechanists on the variables that are most important to successful performance in sprint running highlights the need to bridge
the gap between science and performance through developing the coaching-biomechanics interface (Kerwin & Irwin, 2008).

Lower Limb Analyses

It is apparent from the studies that have investigated the influence of whole-body kinematics on sprint running performance that the lower limbs have the greatest influence on increasing velocity. It is, therefore, not surprising that the majority of research has focused on the lower limbs. Studies that have studied only lower-limb biomechanics have reported similar findings relating to lower-limb kinematics as those discussed in the previous section.

In Ae et al.’s (1992) comparison between elite and university level sprinters, they advocated thigh angular velocity of the support leg during contact as the key kinematic difference. Highlighting this variable supports Mann and Herman’s (1985) theory that favourable values for thigh angular velocity could reduce the effects of braking.

Farley and Gonzalez (1996) concluded that running with higher SF leads to decreased vertical displacement during contact. Whilst this finding was not directly related to performance increases, they discussed how less vertical displacement allows CT to be reduced as there is less negative work that needs to be overcome during the propulsive phase of contact. The authors also attributed increased SF to a reduction in CT of 32%.

Bushnell and Hunter (2007) found a significant difference (p<0.05) between the sprinters and other two groups of distance runners and non-runners for the horizontal distance between the recovery knee and stance knee at TD. They reported that, for the sprint group, the recovery knee was further forward. This finding shows that, despite taking significantly longer steps than the other two groups, the sprinters exhibited faster recovery in preparation for the subsequent TD. This idea was reinforced by the finding that the sprinters obtained a smaller minimum hip angle (i.e. the angle between the trunk and thigh during the final part of the swing phase) than the distance runners and non-runners. A significant difference (p<0.05) was also found between the sprinters and distance runners for
the maximum knee angle at TO, with the distance runners having a greater amount of knee flexion (163°) than the sprinters (151°).

**Summary of Kinematic Variables**

There have been many different kinematic variables advocated in the literature as influencing sprint performance. The large number of kinematic variables associated with successful sprinting is not surprising when considering the number of variables presented by Hunter *et al.* (2004a) as affecting SL and SF (Fig. 2.4). Kinematics during the support phase were identified as the most influential, as this is the time when sprinters can alter their velocity, through the application of force to the track surface, which has a direct impact on the flight phase. A reduction in CT has been associated with increased velocity through the development of increased SF (Farley & Gonzalez, 1996; Luhtanen & Komi, 1978; Mann & Herman, 1985). The inverse relationship between CT and SF is logical given that, along with flight time, CT constitutes step time, the inverse of step frequency. \( y_{TD} \) was also common (Hunter *et al.*, 2004a; Kunz & Kaufmann, 1981; Mann & Herman, 1985), with a reduction being reported as having a positive effect on braking. The earlier termination of contact has been suggested as being beneficial (Bushnell & Hunter, 2007) due to the fact that minimal propulsion is generated during the final phase of contact and, as mentioned above, reducing CT can lead to increased SF.

### 2.4.2 Kinetic Variables

Having considered the kinematic variables that affect SL and SF, the next stage of analysis involves the consideration of the external and internal forces acting on the body that determine the kinematics, namely sprint kinetics. The consideration of kinetics on the body during sprinting can be simplified so that external kinetics affect the kinematics of the body during the support phase and internal kinetics alter the segmental orientation of the body throughout both support and flight phases.

**External Kinetics**

There are two key variables associated with external kinetics, ground reaction force (GRF) and impulse. When GRF is vectorised, vertical forces are responsible for overcoming the gravitational acceleration of the athlete downwards, whereas
horizontal forces are responsible for any changes in the horizontal velocity of the athlete. As reported by Hay (1994) the support phase often starts with a reduction of the athlete’s horizontal velocity caused by the negative horizontal GRF applied to the foot at TD, the braking force. To counteract this braking force the sprinter must then apply a horizontal force backwards so that the resulting GRF propels them forwards. Any change in the athlete’s horizontal TO velocity compared with their velocity at TD depends on the magnitude of the net impulse throughout the support phase.

A kinetic analysis of different phases of sprint runs was performed by Fukunaga et al. (1978). The authors reported that the total external force measured by a force plate changed very little as sprint velocity increased. However, the ratio of horizontal to vertical components did change, with larger horizontal forces being applied during the acceleration phase and larger vertical forces being applied when the athletes were at maximum velocity.

Following on from the work of Fukunaga et al. (1978), Cavanagh and LaFortune (1980) reported a negative correlation of -0.67 between peak vertical force and duration of support during submaximal running. Whilst these results were calculated for distance runners, it seems a logical assumption that the generation of greater peak forces could allow CT to be reduced in sprinters, as the same net impulse could be achieved, required to overcome the negative accelerative effects of gravity. The link between faster running velocity, increased vertical force and reduced CT reported by Fukunaga et al. (1978) and Cavanagh and LaFortune (1980) explains the reduced CT associated with increased running velocity reported by Mero et al. (1992).

Hamill et al. (1983) compared GRF for ten athletes running at velocities of 4, 5, 6 and 7 m·s⁻¹. They observed that for the vertical component of GRF the initial force peak was larger for the two fastest velocities (30.69 and 32.69 N·kg⁻¹ of body mass for velocities of 6 and 7 m·s⁻¹, respectively) than the two slower velocities (20.64 and 25.33 N·kg⁻¹ of body mass for velocities of 4 and 5 m·s⁻¹, respectively). This trend was not continued for the latter stage of support, where vertical GRF was similar across all velocities (~29 N·kg⁻¹ of body mass). The authors also found a similar negative interaction between peak vertical force and CT as Cavanagh and
LaFortune (1980). When looking at the horizontal antero-posterior component of GRF, a marked difference was evident at the different running velocities, with higher running velocities leading to increased GRF. They attributed the increase in horizontal propulsive force to the fact that when running with increased velocity, longer steps are taken; therefore the CM may be further behind the contact foot at TD, resulting in increased braking force that must be overcome.

Mero and Komi (1986) also considered GRF during different running speeds (50 to 110% of voluntary maximum). In their analysis they divided CT into eccentric and concentric phases based on the vertical motion of the CM. They found a positive relationship between running velocity and mean resultant force for both eccentric and concentric phases. For the eccentric phase this positive relationship continued into supramaximal velocity, whereas for the concentric phase there was a reduction in mean resultant force from maximal to supramaximal velocity. It was not possible to compare the results presented by Mero and Komi (1986) to those of Hamill et al. (1983) as mean horizontal force values were not presented in the prior study to allow calculation of mean resultant force.

Mero and Komi (1994) collected GRF data from seven sprinters during the maximum velocity phase. They reported a mean net horizontal impulse of zero, due to equal braking and propulsive impulses of 20 N·s. Mean vertical GRF (31.33 N·kg⁻¹) during braking was close to the maximum value reported by Hamill et al. (1983).

Weyand et al. (2000) reported that, whilst mean GRF during contact increased with faster running velocity, impulse actually decreased as maximum velocity was approached, due to the more influential decrease in CT. Surprisingly, impulses were found to be similar across athletes of different levels when running at maximum velocity. However, it was noted that these impulses were achieved with a variety of combinations of force and CT, with faster runners applying a greater force over a shorter period of time. Through their regression analysis, Weyand et al. (2000) suggested that an increase in support force of one tenth of one body weight (BW) could results in an increase in maximum velocity of 1 m·s⁻¹ due to the potentially greater SF.
Johnson and Buckley (2001) reported horizontal GRF data during the acceleration phase. They reported a mean braking impulse of 6.8 N·s compared with a mean propulsive impulse of 26.3 N·s, resulting in a mean net propulsive impulse of 19.5 N·s. Dividing the mean net impulse reported by the mean body mass of the athletes (69.5 kg) indicates a mean change in horizontal velocity of 0.28 m·s⁻¹ during the contact phase.

Belli et al. (2002) collected GRF data from nine athletes running at velocities ranging from 4.00 to 8.86 m·s⁻¹ (maximal). They reported an increase in peak vertical GRF from 27.78 to 31.91 N·kg⁻¹ as velocity increased, which corresponds to those values previously reported by Hamill et al. (1983). When considering horizontal GRF, Belli et al. (2002) noted an increase from 4.42 to 11.88 N·kg⁻¹ with an increase in running velocity from 4.00 to 8.86 m·s⁻¹. The results of Belli et al. (2002) showed that the percentage increase in peak vertical GRF (~15%) was much less than horizontal GRF (~170%). A possible explanation for the larger percentage increase in horizontal force is that the increase in running velocity leads to larger braking forces, which must in turn be overcome by generating larger propulsive forces later in the stance phase, as suggested by Hamill et al. (1983).

Hunter et al. (2005) collected GRF data from 28 male athletes (mean velocity 8.29 m·s⁻¹) 16 m from the start line. The authors calculated horizontal and vertical impulses, with horizontal impulse sub-divided into braking and propulsive impulses. Hunter et al. (2005) presented impulse values that had been normalised for BW so that they related to changes in velocity, giving them units of m·s⁻¹. Relative vertical impulse was calculated as 0.99 m·s⁻¹, which corresponds to the downwards acceleration due to gravity during a typical flight time of ~0.1 s (0.99 m·s⁻¹ / 9.81 m·s⁻² = ~0.1 s), which must be overcome during contact. The relative horizontal impulse (0.25 m·s⁻¹) was the result of an initial braking impulse of -0.10 m·s⁻¹ followed by a propulsive impulse of 0.35 m·s⁻¹, confirming that the athlete was still accelerating. Based on these findings, Hunter et al. (2005) performed multiple linear regression analyses between velocity and the relative impulses. They reported that 57% of the change in sprint velocity can be explained by propulsive impulse, with a further 7% being explained by braking impulse. Interestingly, vertical velocity did not account for any changes in sprint velocity.
**Internal Kinetics**

Due to the relatively small influence of the upper limbs on sprint performance (Mann & Herman, 1985), the vast majority of research into the internal kinetics of sprinting has focussed on the lower limbs. Mann (1981) extended his analysis of sprint kinetics to include the elbow and shoulder joints. He concluded that the muscle moments around these joints (±~20 to 30 N·m) were drastically less than those of the lower limbs (±~200 to 300 N·m), and that, therefore, the arms did not play a significant role in determining sprint success. It is worth noting that these moments were calculated using a ‘toe-up’ inverse dynamics analysis (IDA) and that once the elbow moment has been calculated the process has already been applied to four previous joints (ankle, knee, hip and shoulder). As errors propagate in IDA, according to the number of joints that the process has been performed on, the errors included in the elbow and shoulder may be much greater than for the lower body. However, in this instance the results were of much less magnitude for the upper limbs than the lower limbs, so the lesser influence of the upper limbs on performance can be accepted, albeit whilst explicit values may contain relatively large errors and should be viewed with caution. Mann (1981) concluded that the role of the arms was to maintain balance whilst the lower limbs propel the body forwards.

Winter (1980) developed the theory of the support moment, being the algebraic sum of the extensor moments of the ankle, knee and hip joints. His theory stated that support is the net extensor moment of the ankle, knee and hip joints and that; as long as the net moment is sufficient for the activity in question, individual joint moments can vary largely. Winter (1980) used the support moment theory to explain how, in certain circumstances, an individual joint can have a negative net support moment throughout stance but collapse is prevented by the positive net support moments generated by the other two joints.

Mann and Sprague (1980) reported a dominance of hip and knee moments during support. Following TD there was an initial period of net concentric hip flexion driving the leg backwards, followed by eccentric flexion as the angular velocity was reduced in preparation for the recovery phase. Knee moment patterns showed initial net concentric flexion, due to weight acceptance, followed by a large eccentric then concentric extension moment as the vertical velocity of the athlete
was reversed in preparation for TO. The net ankle moment was plantar flexion throughout contact, this was initially eccentric as downward motion was arrested and then concentric as upward and forward drive was employed. Mann and Sprague (1980) noted that the hip moment patterns indicated that the sprinters were actively trying to reduce the effects of braking by pulling the CM over the point of contact during the initial stages of contact. They highlighted that the backward driving action of the ground foot immediately after contact places a large stress on the hamstring muscle group, exposing the athletes to potential injury, a notion that was reinforced by the positive relationship between moment at TD and previous hip extensor or knee flexor injury. Furthermore, the authors reported an inverse relationship between the moment at TD and the loss of horizontal velocity during the ground phase, indicating that the large hamstring stress is a requisite of elite performance. The importance of hamstring work is supported by the kinematic finding of Ae et al. (1992), that thigh angular velocity served to reduce the effects of braking at TD, therefore increasing velocity.

Mann (1981) reported similar results to those of Mann and Sprague (1980), showing a dominance of hip and knee moments and similar moment patterns for all three joints. They also noted that the athletes that minimised braking force did so through extensor work at the hip and flexor work at the knee. The role of the ankle musculature was highlighted as being more focussed on arresting downward motion through eccentric contraction than generating upwards or forward motion through concentric contraction.

Vardaxis and Hoshizaki (1989) compared the recovery phase of four advanced and intermediate sprinters. They found that the profile of net joint powers was the same for all athletes, containing the same number of power phases. The hip joint was found to be the primary power generator, whilst the knee served more to absorb and control the power generated from the hip. Hip and knee joint powers were found to be higher for the advanced sprinters than the intermediate sprinters.

Hay (1994) purported that “… athlete’s velocity as the foot leaves the ground (and thus the SL) is a function of the work done by the extensor muscles of the hip, knee and ankle joints during the drive phase.” Hay (1994) discussed the implications of maximising net extensor work by fully extending the joints of the
lower limbs, he concluded that towards the end of the contact phase the extra velocity (and hence, SL) gains are small in comparison to the larger SF obtained by ending the stance phase to reduce CT. Hay (1994) referred to the knee and hip angular values (mean values of 157 and 166°, respectively) presented by Mann and Herman (1985) to demonstrate that elite athletes do not end the stance phase with fully extended lower limbs.

Johnson and Buckley (2001) calculated net joint moments and powers during the mid acceleration phase of repeat 35 m sprints. They reported similar moment patterns to previous studies (Mann, 1981; Mann & Sprague, 1980) for the ankle, knee and hip joints. In addition to joint moment values, Johnson and Buckley (2001) calculated joint power for the three joints. The authors reported similar power magnitudes for the hip and knee during the swing phase, whilst during stance most work was performed at the hip and ankle with mean peak values in excess of 3000 W whilst the knee contributed with a mean peak value of 1544 W. Johnson and Buckley (2001) noted that the timing of peak extensor power was proximal to distal in the joints of the lower limb, the implications of which are discussed in the subsequent section on biarticular muscle function.

Belli et al. (2002) found that the hip joint displayed the greatest increase in peak joint power with increased running velocity, although the reported peak value at maximum velocity (1642 W) was much less than that reported by Johnson and Buckley (2001). Belli et al. (2002) agreed with Vardaxis and Hoshizaki (1989) that the hip joint is the primary power generator and suggested that the role of the knee and ankle extensors is to provide stiffness during contact so that the power produced at the hip is not just absorbed by the other joints, but results in a force being applied to the track surface.

Kuitunen et al. (2002) noted that peak joint moments stayed constant at the ankle, whilst there was a decrease (21.8%) at the knee and increase (44.1%) about the hip as running speed increased. This contrasted with the findings of Arampatzis et al. (1999) who reported increased joint moments at the ankle with increased running velocity. When comparing joint stiffness at the ankle and knee joints, the authors found that mean ankle stiffness remained constant (7 N-m·°⁻¹), whilst stiffness at the knee increased from 17 to 24 N-m·°⁻¹ with increased velocity.
However, it was also noted that ankle stiffness displayed a negative correlation with CT. This value for ankle stiffness is very similar to that previously reported by Stefanyshyn and Nigg (1998) of 7.38 N·m·°⁻¹.

Hunter et al. (2004c) reported joint moments at the ankle, knee and hip very similar in magnitude and pattern to those presented by previous authors (Johnson & Buckley, 2001; Mann, 1981; Mann & Sprague, 1980). The authors also agreed with the finding of Johnson and Buckley (2001) on the proximal to distal transfer of power. Hunter et al. (2004c) noted that a large propulsive GRF coincided with the timings of peak hip and knee extension velocities, indicating the possible increased importance of these two joints over the ankle joint in the development of forward horizontal velocity.

Bezodis et al. (2008) examined joint kinetics during ground contact of the maximal velocity phase of sprint running. They found that the ankle and hip joints perform substantially more work than the knee joint during the ground phase. In contrast to the findings of Johnson and Buckley (2001) and Mann and Sprague (1980), Bezodis et al. (2008) reported relatively low knee extensor moments with normalised values being approximately half those reported in previous studies (Belli et al., 2002; Johnson & Buckley, 2001). The authors speculated that this may suggest that the role of the knee is to transfer the moments generated at the hip downwards towards the ground, as hypothesised by Johnson and Buckley (2001).

Biarticular Muscles
When performing an IDA, net moments are calculated around a joint based on the moment present at the previous joint in the analysis (see Section 2.6.4). The transfer of force from one joint to the next is partly performed by the muscles of the lower limbs. Whilst the role of the muscles can be simplified for the analysis of net kinetics at each joint, particular interest should be given to the biarticular muscles, the hamstrings, rectus femoris and gastrocnemius. Andrews (1987) discussed the paradoxical function of the hamstring and rectus femoris, due to their producing opposing moments at hip and knee. Andrews (1987) also noted, however, that similar movements often occur at the hip and knee joints (i.e. flexion of one and simultaneous extension of the other).
Bobbert and van Ingen Schenau (1988) proposed that the role of the biarticular muscles is to transport energy from the hip to the ankle during vertical jumping, which is similar to the extension phase of a sprint running step. Developing the idea of Bobbert and van Ingen Schenau (1988), Jacobs and van Ingen Schenau (1992) reported a similar role of the biarticular muscles during sprint starts, with a distal transfer of power generated at proximal joints so that the associated forces were applied to the track surface. This finding was reflected by another study by Jacobs et al. (1996), which studied vertical jumping and the accelerative phase of sprint running. Jacobs et al. (1996) concluded that the large monoarticular muscles (i.e. the gluteus maximus) acting at the proximal joints produce large amounts of power, which is transferred along the chain of lower-limb joints by smaller biarticular muscles, so that it is efficiently applied to the track surface. Further support of the idea of proximal to distal power transfer was apparent in the results of Johnson and Buckley (2001), who noted that the timing of peak extensor power was proximal to distal.

The effects of the biarticular muscles on injury were investigated by Kameyama et al. (1994). The authors found that the biarticular muscles placed large stresses on the hip and knee joints but that the concentration of muscular stresses depended on the joint angles at the time of greatest biarticular muscular activation.

Kyröläinen et al. (2005) examined electromyographic activity during running. They reported that the biarticular muscles perform eccentric work during the swing phase and concentric work during the ground contact phase. The electromyographic values calculated by Kyröläinen et al. (2005) were greater than the maximal voluntary contraction for the biarticular muscles, indicating that their role in storing and releasing elastic energy also contributes to the forward motion of the athlete.

2.4.3 Performance Variability
When quantifying asymmetry, it is important that natural inter-step variability is considered for each athlete (Giakas & Baltzopoulos, 1997b). For an athlete to display asymmetry, the differences between sides must be larger than the intra-side differences.
Salo and Grimshaw (1998) calculated kinematic variability during sprint hurdle clearance. They reported coefficient of variation (CV) values of 1.5% for velocity and 2.5% for SL for male athletes during hurdle clearance. Hunter et al. (2004b) calculated variability for sprint runners and reported similar CV values to Salo and Grimshaw (1998) for SV (1.0%) and SL (2.1%). Hunter et al. (2004b) also calculated CV for other variables that they considered important determinants of SL and SF (Hunter et al., 2004a) and found that CV values were largest for $y_{TD}$ (9.0%) and variables derived from the vertical displacement of the CM, such as CM TO height (34.6%). When considering the findings of Hunter et al. (2004b), it is important to note that no mention of asymmetry was made and it was not specified whether or not data were collected from the same side for repeat trials. Therefore, it could be that some of the variability reported by Hunter et al. (2004b) is actually a consequence of asymmetry present within the athletes analysed.

Bradshaw et al. (2007) assessed the performance variability of 10 well trained sprinters over four maximal effort sprint starts. They found variability to alter both between sprinters and between variables analysed. Variability in time taken to reach 10 m from the start showed very low levels of variability with biological CV ranging from 0.12 to 0.97%. However, variability was reported to be much larger for some kinematic variables, with large biological CV values reported for angular velocity of the hip (54.1%) and ankle (34.3%) for some athletes. Using a linear regression model, Bradshaw et al. (2007) found horizontal block-leaving velocity and lead ankle angular velocity to be the variables best associated with increased 10 m sprint performance. However, of the two variables identified the function of variability was not the same; for block-leaving velocity, reduced variability was desirable, whereas the opposite was the case for lead ankle angular velocity. The authors speculated that, contrary to traditional belief, increased variability may be beneficial as it allows the sprinter to be able to adapt to changes in environmental and performance factors that are present when performing in different competitions.

Gittoes and Wilson (2010) investigated variability of intralimb joint coordination during sprint running and found that the knee-ankle joint coupling displayed less variability than the hip-knee coupling. The authors suggested that the greater
consistency shown by the knee-ankle coupling could indicate a greater predisposition of the knee and ankle joints to overuse injury.

2.4.4 Contemporary Perspectives in Elite Sprint Running
At the 2008 Olympic Games in Beijing, the current World and Olympic 100 m champion broke the 100 and 200 m world records as well as being part of the world record breaking 100 m relay team. The phenomenal success of this athlete, along with the apparent ease of his 100 m success, prompted an investigation by Eriksen et al. (2009) into how fast the athlete could have run if he had not decelerated before the finish line whilst celebrating. Eriksen et al. (2009) used calibration marks visible in broadcast video footage of the 100 m race to calculate the velocity of the champion relative to other athletes in the race. The authors concluded that if the champion had continued to maintain a higher acceleration than the second place finisher, a time of 9.55 s may have been within reach, 0.14 s faster than the actual time of 9.69 s.

Following the predicted potential time of the Olympic 100 m champion by Eriksen et al. (2009), the same athlete competed in the 2009 World Championships in Berlin. The Olympic champion won the 100 m final at the World Championships and, in doing so, broke his own world record by a staggering 0.11 s. The new world record of 9.58 s was close to the value of 9.55 s predicted by Eriksen et al. (2009). However, during the 100 m final of the 2009 World Championships the athletes benefitted from a tailwind of 0.09 m·s⁻¹. Helene and Yamashita (2010) modelled the winning athlete’s performances in the Olympic and World Championship 100 m finals to estimate the maximum acceleration and power and total mechanical energy produced in both races. Helene and Yamashita (2010) were surprised by their findings, that the athlete produced larger values for all three measures during the slower Olympic Games performance. They then utilised their model to combine the accelerative performance of the athlete during the Olympic Games final with the 0.09 m·s⁻¹ tailwind present at the World Championships to predict that the athlete could have reduced the record achieved during the Olympic Games to 9.53 s with a favourable tailwind and if he had not decelerated before the finish line whilst celebrating.
Beneke and Taylor (2010) analysed the technique of the World and Olympic champion. They noted, from counting the number of steps that the athlete took to cover the 100 m distance in the 2009 World Championships, that he achieves success through exhibiting a larger SL than other world class sprint runners and below-average SF. Beneke and Taylor (2010) did not report SL values, but presented SF values of 4.28 Hz for the champion, compared with a mean value of 4.54 Hz for the other finalists in the 2009 World Championships. The authors theorised that by running with a shorter SF, whilst maintaining a high velocity via a large SL due to a greater amount of mechanical power development, the current champion is more biomechanically efficient than other world class sprint runners.

2.4.5 Summary
Despite the wealth of published literature on SL and SF, there is some disagreement as to which factor limits performance. More recent suggestions that each athlete has an optimal combination of SL and SF and that increases in SF can be achieved in the short term whilst SL increases require more time seem rational. There is more agreement in the literature concerning kinematic factors affecting performance, with recurring themes, such as \( y_{TD} \). Kinetic studies have also tended to agree for both external and internal kinetics, with the large musculature surrounding the hip joint being advocated as the main power generator and the smaller muscles of the lower limbs being used to transfer the forces generated at the hip to the track surface.

2.5 Bilateral Asymmetry
The issue of bilateral asymmetry in sprinting is one that has been the focus of surprisingly little research. To the author’s knowledge, there is very little published research on kinematic asymmetry during sprinting and none on kinetic asymmetry. This is an area that, as well as having potential influences on performance, has strong implications on what conclusions can be drawn from unilateral experimental data and the methodological considerations made when planning an experiment. Due to the lack of research into sprinting asymmetry, it has been necessary to broaden the review for this section to include investigations of slower running speeds and walking studies. To allow comparison between studies using different methods to quantify asymmetry, \( \theta_{SYM} \) values have been calculated where possible.
from the data presented by the authors. The method for the calculation of $\theta_{SYM}$ is presented in Section 2.6.4 of this chapter. An alternative measure of asymmetry that has been presented by some authors is the symmetry index (SI), which can be liable to artificial inflation of asymmetry values (Herzog et al., 1989), as discussed in Section 2.6.4.

2.5.1 Running

Cavanagh et al. (1985) profiled a range of kinematic variables for two elite distance runners. They considered asymmetry of the variables analysed, however they did not actually calculate an explicit measure of asymmetry. Cavanagh et al. (1985) found that asymmetry varied between the two athletes, for example Athlete A’s supination at footstrike was 24.6° for the right foot and 18.5° for the left foot ($\theta_{SYM} = 8.95\%$), whilst Athlete B’s supination at footstrike was said to be bilaterally similar, although specific values were not reported for the second athlete. When analysing asymmetry of peak GRF, Cavanagh et al. (1985) reported that athlete A exhibited similar values of approximately 3 BW for the left and right sides following TD, whereas Athlete B generated a GRF of over 4.1 BW on the right side compared with just 2.7 BW on the left side ($\theta_{SYM} = 12.9\%$). Cavanagh et al. (1985) suggested that the asymmetry in peak GRF exhibited by Athlete B could have serious implications on injury potential for the overloaded right side.

Asymmetries in GRF data were noted by Munro et al. (1987). The authors did not report separate left and right values, but presented graphical GRF patterns for both limbs of two athletes. One of the athletes discussed showed greater consistency for the GRF of the left leg when running at different speeds whilst the GRF measured for the right leg altered as running speed increased from 3.0 to 5.5 m·s$^{-1}$. The second athlete considered in the asymmetry analysis recorded larger peak GRF values for the left limb over those for the right limb at all velocities measured.

Vagenas and Hoshizaki (1991) analysed 29 male long distance runners during treadmill running at their usual training pace. Their analysis focussed on the ankle region, where they found high levels of asymmetry across runners for many angles and angular velocities relating to the ankle joint. They concluded that when
planning for data collection from runners, it is not suitable to collect data from just one side and assume that symmetry exists.

Conversely, Karamanidis et al. (2003) assessed running asymmetry in female long distance runners, during treadmill running. They found that linear hip displacement and angular knee and ankle displacement has SI values of $<10\%$, whereas angular velocity parameters for all joints and flight times had SI values of $>15\%$. The authors concluded that for certain kinematic values, collecting unilateral data with the assumption of symmetry is acceptable but that this is not the case for all variables, such as angular velocity.

Jacobs et al. (2005) measured the hip abductor strength and fatigability of the dominant and non-dominant legs of males and females. They found that strength differences were apparent between dominant and non-dominant sides with a mean dominant peak torque value of 81.0 N·m compared with 76.1 N·m for the non-dominant limb. The authors cited that a strength imbalance in athletes, despite being relatively small, could be a potential cause of future injury or predispose one side of the body to injury more than the other. Fatigability was found to be symmetrical between the sides.

In a recent study into the braking and propulsive phases of sprint running, Ciacci et al. (2010) stated that they had performed a preliminary assessment of asymmetry of the variables that they were analysing. The authors did not present any asymmetry results, but noted that no differences were apparent between the left and right sides. The inclusion of a preliminary test of asymmetry prior to data collection allows greater conclusions to be made about an athlete’s technique based on data collected from one limb. However, in the study by Ciacci et al. (2010) not all the athletes that were included in the study were tested for asymmetry and, as demonstrated by Cavanagh et al. (1985), asymmetry can vary by a large amount between athletes.

2.5.2 Walking

Gundersen et al. (1989) investigated the kinematic symmetry of the knee and ankle during walking, with the aim of relating asymmetry to limb dominance. Limb dominance was assessed through a series of lab-based tests including kicking
accuracy and balance tests. They reported that there were varying levels of asymmetry across subjects and that there was no relationship between asymmetry and limb dominance. This resulted in group mean dominant and non-dominant values showing low levels of asymmetry. However, when considering variables on an individual subject basis, asymmetries were apparent but varied between limbs. An example of this is with maximum knee extension, where the group mean \( \theta_{SYM} \) value was 0.31% compared with subject 5 who had a \( \theta_{SYM} \) of 2.75% with the dominant limb having a larger value whereas subject 14 had a \( \theta_{SYM} \) of 1.23% but with the non-dominant limb displaying the larger value.

Herzog et al. (1989) reported the symmetry of GRF patterns during walking, using the symmetry index proposed by Robinson et al. (1987), which is discussed in the quantification of asymmetry section of this review. Herzog et al. (1989) reported that vertical components of GRF (including peak force, loading time and impulse) displayed SI values of within 4% with most values being less than 1%, with 0% representing no asymmetry. Similar results were found for antero-posterior components of GRF with all but two values being within 4%. One of the values outside of that range (total impulse) highlights the potential flaws with the use of the SI, where a small initial value resulted in a SI of over 700%. When comparing medio-lateral GRF asymmetry, results indicated greater asymmetry than antero-posterior GRF, with most variables having a SI greater than 10%.

Giakas and Baltzopoulos (1997b) investigated symmetry and variability of GRF during walking. The authors collected data from 20 trials for each side for ten subjects, reporting that asymmetry was low for many variables during walking. Medio-lateral aspects were the exception, with the timing of peak forces displaying asymmetries equivalent to \( \theta_{SYM} \) values of 6.68%. However, Giakas and Baltzopoulos (1997b) noted a large amount of variability in the medio-lateral force data, suggesting that this could have influenced the apparent asymmetry.

Sadeghi et al. (2000) reported asymmetry in able-bodied gait. The authors noted that gait symmetry has often been assumed to simplify data collection and analysis, but they did not endorse the assumption of symmetry, as asymmetry had been reported in many studies. Sadeghi et al. (2000) went on to discuss possible causes of gait asymmetry and suggested that the ambulation of the human body is
carried out by the preferred limb, with the contralateral limb providing support for the movement required during the recovery of the favoured limb.

2.5.3 Amputees
Analyses of asymmetry have often formed part of investigations of unilateral amputees (Brüggemann et al., 2008; Buckley, 1999; Burkett et al., 2003; Wilson et al., 2009). The inclusion of asymmetry in such analyses is common due to the physiological asymmetry of such athletes. Investigations of unilateral amputees allow direct comparison between an affected and intact limb within a subject (Hillery & Wallace, 2000) so that the effects of the prosthesis on technique can be compared to the intact limb.

Sanderson and Martin (1996) performed a kinematic and kinetic analysis of unilateral trans-tibial amputee athletes and able bodied athletes during submaximal running (2.70 to 3.50 m∙s\(^{-1}\)). They reported that joint angle profiles for the knee and hip were similar for intact and prosthetic legs, with slight differences in the range of motion. Results for the ankle joint showed more asymmetry, with the prosthetic limb displaying little dorsiflexion. In contrast, when comparing the joint moments for the amputees intact and prosthetic legs the ankle moment was found to be most similar, with the knee moment for both limbs following a similar pattern during stance and flight whilst the hip moment was the most asymmetrical.

Buckley (1999) also compared bilateral lower-limb kinematics of elite unilateral amputee sprinters. It is interesting to note that the study design also included comparison of amputee sprinters with able-bodied sprinters; however, whilst asymmetry of the amputee sprinters was investigated, symmetry was assumed for the able-bodied sprint group and therefore data were only collected unilaterally for these athletes. Buckley (1999) reported that kinematic asymmetry of the lower limbs was high for the trans-femoral amputee tested and much less for the trans-tibial amputees. Although asymmetry was not quantified, Buckley (1999) suggested that the use of the prostheses enabled the trans-tibial amputee athletes to achieve similar kinematics for both limbs. However, it was noted that the range of motion at the joints, was reduced for the prosthetic limb.
Recently, much attention has been given to the analysis of amputee sprinting due to controversy surrounding the eligibility of amputee athletes to compete in able-bodied competition (Eason, 2008). Two investigations which arose from the debate surrounding the eligibility of amputee sprinters in able-bodied competition were those of Brüggemann et al. (2008) and Weyand et al. (2009). These two studies assessed different factors relating to the sprint performance of an international bilateral trans-tibial amputee athlete. Such a study was required at the time due to the performance level of the amputee sprinter allowing him to compete at an elite level against able-bodied sprinters, a phenomenon which had not occurred until then. One possible explanation for the superior performance of this athlete over other amputees is the fact that asymmetry is reduced for the bilateral amputee compared to other unilateral amputee athletes. Due to the differing mechanical demands of intact and prosthetic limbs during sprinting (Weyand et al., 2009), unilateral amputees may have to adapt to the different mechanical demands of one limb whilst maintaining a different technique for the intact limb, whilst a bilateral amputee can focus solely on optimising a symmetrical sprinting technique.

Wilson et al. (2009) investigated how lower limb asymmetry of two unilateral amputee sprint runners was affected by prosthetic adjustments. They reported that changes to prosthetic foot height led to significant changes for both athletes in asymmetry for contact time, the change in angle between the ground leg and the track during contact, vertical stiffness and the peak vertical CM displacement. Effects of changes to stiffness characteristics of the prostheses were also investigated and found to cause a significant difference for both athletes in asymmetry for leg stiffness and the change in leg length during contact.

2.5.4 Summary
Previous studies have analysed biomechanical asymmetry of sub-maximal running and walking in able-bodied participants and sprint running in amputee athletes. The range of applications used for the analysis of bilateral asymmetry highlights the usefulness of quantifying asymmetry from a performance perspective (Vagenas & Hoshizaki, 1991), an injury perspective (Jacobs et al., 2005) and a sports technology perspective (Buckley, 2000). Therefore, asymmetry analyses
could be utilised to bridge the gap between coaching and biomechanics, which was discussed by Kerwin and Irwin (2008).

2.6 Methods of Approach

2.6.1 Research Approach
Different approaches are available for addressing research questions on the biomechanics of sprint running. Yeadon and Challis (1994) identified two separate methods of approach; experimental, where movement data are used to answer research questions relating to technique and theoretical, involving the modelling of hypothetical movement data to examine specific controlled movements. Robertson et al. (2004) discussed disadvantages to experimental approaches that can be overcome when using forwards dynamics analyses, including isolation of variables to be altered, less complexity than human participants and the ability to perform many repetitions without inducing fatigue, all of which can be problematic when an experimental approach is used. However, theoretical approaches often utilise models that are not fully representative of the system being investigated, which can lead to errors in conclusions drawn from them. Robertson et al. (2004) noted that “the best way to obtain human movement data...[is] to collect it from human subjects”.

2.6.2 Methods of Data Collection and Processing
There are numerous data collection methods that can be employed for the collection of biomechanical data. Most of these have their own strengths and weaknesses that advocate their use, such as intrusiveness on performance, accuracy, cost, availability and data collection and processing time. In most cases there is not one method that is superior in every factor and usually a compromise must be made to select the most suitable method for the specific research needs. Recent advancements in technology have led to the development of more contemporary methods of data collection for use in sprint running (Cheng et al., 2010).

2.6.2.1 Kinematic Data Collection Techniques
There are many different approaches available for the collection of kinematic data each with their own inherent strengths and weaknesses. The first division is
between automated (marker based) and manual (digitised) data collection systems. There are further divisions that can be made regarding different methods of automated and manual systems, which are discussed in the subsequent sections.

**Automated Data Collection**

Automated systems are capable of taking very accurate and precise measurements (Richards, 1999). Following calibration and alignment, automated systems allow large amounts of data to be collected and reviewed with very little time delay, allowing near-instant feedback of basic observations to a coach or performer. One limitation of automated systems is the fact that a fixed volume has to be defined and calibrated before data can be collected and that, due to the cost associated with such systems, there is often a limit on the possible extension of data collection volumes through the addition of extra cameras or scanners as is more often the case with video-based methods. The restricted data collection volume means that for events covering a large area, such as sprinting, data for an entire race cannot be collected in one session and instead a race has to be broken down into phases for analysis. Another drawback to automated systems is the fact that the vast majority of systems require the participant to wear markers, which can be unappealing to athletes, especially those of elite level. Furthermore, due to the requirements to place markers on participants and to surround the data capture volume with scanners, automated systems are not suitable for the collection of data in competition and, to the knowledge of this author, this has not been performed to date.

There are two categories of automated motion analyses system, active (e.g. CODA) and passive (e.g. VICON), referring to the markers that are tracked by the system. Both types of system track low frequency light, namely infra-red. Active systems track markers which contain their own light source, therefore requiring their own power source. Active markers are individually coded allowing them to be distinguished by the system. Conversely, passive markers need no power source as they reflect light emitted from the scanning units. This reduces the mass of the markers but can cause problems with marker identification and the introduction of ‘ghost’ markers when light is reflected by other objects close to the data collection area. Further differences are apparent in the methods employed by the systems
for the calculation of 3D coordinate data. Passive systems require markers to be in view of 2 or more cameras for positions to be calculated. Positional data are then calculated via the implementation of direct linear transformation (DLT) or a similar process. For most active systems, each scanner contains three sensors, each of which must be able to detect the markers. Marker positional data is then calculated by triangulation as the exact location of each sensor within the scanner unit is known. Active systems are pre-calibrated and simply need aligning to the laboratory space or data collection volume, whereas passive systems must be calibrated so that the location of each camera relative to the others can be determined before each data collection session.

**Manual Data Collection**

The most common form of manual, kinematic data collection is the use of video capture. Scaling and DLT are common methods used for the reconstruction of digitised video images; these methods are discussed in the following section.

Coordinate data can be calculated via digitised video images to provide Cartesian locations of joint centres and other landmarks of interest. The data collection process for trials to be digitised requires a defined area to be calibrated. The size of the data capture volume is limited by the field of view of a camera. It is possible to extend the field of view via additional cameras; however, each of these require independent calibration. The accuracy and precision of data calculated from digitising has been proven to be acceptably high, with Kerwin (1995) reporting a precision of \(2.5 \times 10^{-3}\) m. The associated cost of video cameras and digitising software is significantly less than that of automated motion capture systems. The main drawback with the process is the time taken to digitise video images. Depending on the number of digitised points and the complexity of the movement being analysed, digitisation can take \(~500\) times longer to perform than the length of the movement of interest. Salo and Grimshaw (1998) assessed the variability associated with manual data collection in sprint hurdles. They showed that variance in repeated digitisations of a hurdle clearance could be as low as 2%.

**Methods of Kinematic Segment Tracking**

Historically, the vast majority of kinematic data collected on sprinting has involved the estimation of joint centre locations based on either markers positioned on soft
tissue surrounding the joint or estimation from manual digitising. This method can lead to errors due to incorrect estimation of joint centre location, marker placement not being fully representative of joint centres, joint movements being hindered by markers positioned on joints and the inability to track internal segment rotation. Reinschmidt, van den Bogert, Nigg et al. (1997) examined the error associated with external markers. They found that the agreement between markers located on the skin and markers attached to bone varied from very high for flexion and extension to virtually no agreement for internal and external rotation. To overcome this, recent research has utilised ‘segmental clusters’ that were previously used in clinical gait analysis, to allow calculation of internal segment rotation.

Segmental clusters allow the estimation of actual joint centre locations from static standing trials. The estimated joint centre can then be tracked throughout movements by clusters located around the midpoint of segments. Advantages to using segmental clusters include less restriction of movement at the joints, the ability to track internal rotation and the ability to estimate joint centre locations rather than having to rely on data collected from individual markers located on soft tissue around the joint. One disadvantage to using segmental clusters is the need for more markers to be placed on the participant, which may be limited with some automated systems. Segmental clusters also introduce logistical challenges relating to the placement of clusters on segmental midpoints, due to the size and shape of limb segments (i.e. mostly cones) there can be a tendency for clusters to slide towards the narrower end of a segment, especially under the ‘capillary wave’ type action apparent during repeated muscle activation.

McClay and Manal (1999) investigated the importance of secondary planes of motion when analysing submaximal running using segmental clusters. They reported that the majority of movement and work occurs in the sagittal plane. However, McClay and Manal (1999) calculated that ~20% of work at the knee occurred in the frontal plane, with ~6% occurring in the transverse plane, thus highlighting the potential importance of considering other planes of motion.

Recently, Slawinski et al. (2010) calculated 3D angular velocity and kinetic energy during the sprint start. They reported that maximal joint angular velocity at the hip joint was achieved through a combination of flexion-extension, abduction-
adduction and internal-external rotation. Therefore, the authors recommended that the complex movements of the sprint start should be analysed in 3D.

Cluster Design
Cluster design can vary greatly, allowing the most appropriate solution to be found for each research requirement. Cappozzo et al. (1997) considered the criteria for segmental clusters in terms of markers required, size and shape. They found that whilst a minimum of three markers is required to be able to track orientation of a segment, orientation error decreased with an increased number of markers. Therefore, the authors suggested that four or more markers should be used for each cluster. Cappozzo et al. (1997) didn’t make a specific size recommendation, stating that a cluster should be a large as possible. They did note that if the size of the cluster is less than ten times the experimental error of the system, the orientation error increases dramatically. The use of clusters for the collection of kinematic data has the benefits of allowing calculation of internal joint rotations. However, due to the increased size of clusters (approximately 0.10 x 0.16 m) relative to surface anatomical markers (approximately 0.01 x 0.01 m) and the fact that clusters are attached near the middle of segments where the amount of soft tissue is largest, the use if clusters is limited in some high impact activities, such as maximal velocity sprint running.

2.6.2.2 Kinetic Data Collection Techniques

Ground Reaction Force Data Collection
GRF and centre of pressure (COP) data, relating to the point of force application, provide information relating to the nature of the ground contact phase and are also required inputs into inverse dynamic equations for the calculation of net joint moments. GRF data are usually collected via force plates, which can be mounted under the surface of a running track or walkway. There are two main standards of force plate used for the collection of GRF in sprint running, namely piezoelectric and strain gauge.

Piezoelectric force plates have a reported resolution of 10 mN (Kistler Instruments Ltd., UK) and an accuracy of ~1% (Kerwin, 1997). An inherent difficulty with force plate data collection is the need for foot contacts to occur within the plate boundaries. The occurrence of foot contacts overlapping or outside of plate
boundaries can lead to rejected trials (Bezodis et al., 2008; Johnson & Buckley, 2001), increasing the required number of trials to allow collection of sufficient data.

Bobbert and Schamhardt (1990) investigated the accuracy of COP calculation at different locations on the surface of a piezoelectric force plate. They reported that the amount of error in the calculated COP location increased substantially when force was applied towards the corners of the plate, outside of the force sensors.

A large force plate (0.90 x 0.60 m) covers less than half of a typical 2 m SL, which results in the need for many trials to be performed when collecting GRF data. Challis (2001) investigated the effect of force plate targeting, which is the conscious shortening or lengthening of SL to ensure contact is made with the force plate. Challis (2001) found that some temporal and GRF data were different for some trials where longer or shorter than usual steps were taken, concluding that force plate targeting may have negative effects of data collection depending on the variables being analysed.

Studies that have collected GRF data during sprint running have often ensured that athletes did not alter their step pattern whilst approaching the force plate (Bezodis et al., 2008; Hunter et al., 2004c; Johnson & Buckley, 2001). Another approach that was taken by Mann (1981) was the use of a visual check mark located on the running track 10 m before the filming area for the athletes to target. The location of the check mark was altered if necessary during warm-up runs so that the athletes contacted the force plate. The effect of using a check mark in this way increasing the occurrence of contacts with the force plate, whilst the kinematic and kinetic differences caused by targeting were hopefully overcome in the 10 m that the athletes covered before data collection began.

Wong et al. (2009) investigated the calculation of joint moments for foot contacts that occurred across two force plates during walking gait. The authors noted that the variability that occurred between contacts from the same foot occurring on one plate and between two plates was less than a third of the variability that occurred between left and right foot contacts. This finding indicates that it may be possible to increase the occurrence of foot contacts using multiple force plates mounted end-to-end.
2.6.2.3 Sampling Rates

Sampling rates used in sprinting research have ranged from 50 Hz (Bezodis et al., 2008; Gajer et al., 1999; Johnson & Buckley, 2001) to 250 Hz (Slawinski et al., 2008) for kinematic data, whilst kinetic data is generally collected at much higher sampling rates of around 1000 Hz (Bezodis et al., 2008; Mero & Komi, 1994; Weyand et al., 2000). It is important that the sampling rate is at least twice as high as the highest frequency contained within the movement being analysed to ensure that aliasing effects are not present within the data (Winter, 2009). Whilst there are advantages to collecting data at higher sampling frequencies, a trade off must often be made between the sampling rate and processing time or other inherent system limitations. For example the CODA system (Charwood Dynamics, Leicester, UK) can only collect data at its maximum sampling frequency of 800 Hz from six or fewer markers. Therefore, if more markers are required, a lower sampling rate must be used. Dainty (1987) noted that the required sampling frequency of a movement depends on the frequency of the movement itself. Johnson and Buckley (2001) justified the use of 50 Hz video capture with the fact that gross body movements tend to involve frequencies up to 10 Hz (Lees, 1980), therefore 50 Hz video provides a sampling rate that is five times greater than the frequency of the movement.

2.6.2.4 Data Processing

*Coordinate Reconstruction*

The transformation of image data to 2D or 3D coordinate data is required for image based motion analysis. Scaling has been used historically for the calculation of 2D coordinate data (Jacobs & van Ingen Schenau, 1992; Johnson & Buckley, 2001; Mann, 1981), due to the relatively planar nature of sprint running. One environmental demand associated with the scaling method is the need for the image plane to be parallel to the movement plane of interest (Yeadon & Challis, 1994). DLT is another method that has been utilised to calculate 2D coordinate data in investigations of sprint running (Bezodis et al., 2008).

DLT is an alternative method to scaling, that offers greater flexibility in camera location and also has a reportedly greater accuracy (Brewin & Kerwin, 2003). DLT was originally developed by Abdel-Aziz and Karrara (1971) for coordinate reconstruction in three dimensions. 3D-DLT uses a minimum of 11 DLT
parameters, each a function of a geometric parameter, to define the geometry and internal characteristics of each camera. A 12\textsuperscript{th} DLT parameter is often included for lens correction, which rectifies errors caused by the curvature of the camera lens (Brewin & Kerwin, 2003). 2D-DLT uses a minimum of eight parameters to project known locations of calibration points onto a plane. As with 3D-DLT, an additional lens correction parameter can be included in 2D-DLT (Walton, 1981).

**Noise Reduction**

When kinematic and kinetic data are collected, the effect of noise within the data must be considered. Noise can be introduced into the data from many sources such as electrical signals, light interference and soft tissue movement. The effects of noise contained within raw data are increased following each differential iteration (Wood, 1982), such as when calculating velocity from displacement data. Therefore, to allow meaningful conclusions to be drawn, noise contained within the raw data must be minimised. Various methods are available to reduce the effects of noise within data, including polynomial approximations, spline functions or digital filters (Wood, 1982). The Butterworth digital filter is very often used on biomechanical data. This can take the form of low-pass, high-pass and band-pass, each allowing data of predetermined frequencies to ‘pass’ through the filter and effectively removing the effects of other frequencies (Winter, 2009).

Due to the nature of human movement, being of relatively low frequency, a common filtering method is a fourth-order low-pass Butterworth filter (Yu et al., 1999). The selection of the optimum cut-off frequency to filter data has been the topic of much research (Challis, 1999; Giakas & Baltzopoulos, 1997a; Winter, 2009). A widely accepted method for the selection of a suitable cut-off frequency is Winter's (2009) residual analysis (Bezodis et al., 2008; Hunter et al., 2004b). This involves visual inspection of a residual-frequency graph to select the most appropriate cut-off frequency for the data set. This method, whilst being widely accepted and recommended, is highly labour intensive and can be less appealing than other techniques due to the subjectivity of having to visually assess the curves of a graph (Challis, 1999). One alternative was suggested by Challis (1999) to overcome the subjective nature of the analysis. Challis' (1999) method uses the ‘autocorrelation function’ to determine the most appropriate cut-off frequency, based on the frequency that returns the lowest autocorrelation value. This
overcomes both disadvantages of Winter’s (2009) method as the function can be written into computer script allowing rapid computation of multiple data sets and it offers a more objective alternative to the selection of cut-off frequencies.

2.6.3 Inertia Profiling

Estimations of body segment inertia parameters (BSIP) have been performed using numerous methods to allow estimation of segmental masses, CM location and moments of inertia, through the use of average weightings provided for each segment relative to the whole body. BSIP models have been developed using a number of methods.

Dempster (1955) developed an early model, based on segment masses and lengths measured from dissected cadavers, a method that has since been repeated (Chandler et al., 1975; Clauser et al., 1969). The use of cadavers to collect inertia data has the benefits of taking a small amount of time to collect the relevant data; however, the data collected from such methods can be questionable due to the size and former health of the subjects. Yeadon and Challis (1994) noted that the use of cadaver data to extrapolate BSIP values to healthy sporting populations may lead to errors due to physiological differences.

Mathematical modelling has been used to estimate BSIP based on segmental shapes and sizes and density values calculated from cadaver based studies (e.g. Hatze, 1980; Jensen, 1978; Yeadon, 1990). Whilst the accuracy of such methods is reportedly high, predicting body mass to within 3%, there are drawbacks to such methods such as the large amount of time taken to collect required measurements from the participants. Another potential limitation of mathematical models for the calculation of BSIP values is the assumption of uniform density (Yeadon, 1990).

Medical imaging techniques, such as gamma-mass scanning employed by Zatsiorsky and Seluyanov (1983), offer the advantage of enabling the calculation of tissue distribution within the body. However, use of such methods is restricted due to availability and cost of the complex equipment required. Zatsiorsky and Seluyanov (1983) collected BSIP data from a young athletic population, making the relevance of the resulting data greater than that collected from cadavers.
De Leva (1996) addressed a problem with the results presented by Zatsiorsky and Seluyanov (1983) that their BSIP values related to bony landmarks at the segment extremities, rather than the joint centre locations commonly used in biomechanical analyses. De Leva (1996) presented adjusted BSIP values from those reported by Zatsiorsky and Seluyanov (1983), which related to joint centres. However, the adapted BSIP values presented by de Leva (1996) contained a different distal endpoint of the shank segment to the proximal endpoint of the foot segment. To overcome this problem, Hunter et al. (2004c) used the BSIP values presented by de Leva (1996) with the exception of the foot segment, for which they used the values calculated by Dempster (1955), since Dempster’s (1955) model used the same proximal endpoint of the foot segment as the distal endpoint of the shank segment in de Leva’s (1996) model. Furthermore, Hunter (2004c) added a mass of 0.20 kg to the foot segments, to represent the mass of a typical running spike.

Bezodis (2006) compared the inertia models of Zatsiorsky and Seluyanov (1983), de Leva (1996) and Yeadon (1990) for the calculation of gravitational acceleration based on the freefall of two athletic male’s CM locations whilst orientating their body segments in different positions similar to those that would occur during sprint running. The results showed that that there were very small differences between the methods, with the cause of the observed differences being mainly due to the variation in the definition of the lower-limb segments between Yeadon’s (1990) model and the other two. Bezodis (2006) concluded that, in light of the added time demands associated with Yeadon’s (1990) model and the location of the segmental endpoints proposed by Zatsiorsky and Seluyanov (1983), the most suitable model for use in the analysis of sprint running is that of de Leva (1996), combined with the foot segment presented by Dempster (1955).

2.6.4 Data Analysis Techniques

*Inverse Dynamics Analysis*

An IDA has been utilised in many studies to calculate net joint moments during sprint running (e.g. Belli *et al.*, 2002; Bezodis *et al.*, 2008; Hunter *et al.*, 2004c; Johnson & Buckley, 2001). Belli *et al.* (2002) investigated the suitability of an IDA for the calculation of muscle moments and powers at the ankle, knee and hip joints during running. Belli *et al.* (2002) discussed the possibility of error introduced in the IDA method due to assumptions of rigidity of the body segments. However, the
authors concluded that, due to the repeatability of kinetic results, an IDA is a useful method for the summation of net joint moments and powers.

IDA inputs include both kinematic and kinetic data. These data tend to be collected using independent motion analysis systems for kinematic data and force plates for kinetic data. The use of different systems for the collection of kinematic and kinetic data often means that the two types of data are sampled at different rates and that each includes different frequencies of noise. Bisseling and Hof (2006) noted that kinematic and kinetic IDA inputs should be filtered using the same cut-off frequency, highlighted the potential errors that may be introduced when separate cut-off frequencies are utilised. The authors noted that false impact peaks could be introduced into the IDA due to high frequency components remaining in the kinetic data whilst the respective high frequency accelerative components are removed from the kinematic data via the low-pass filtering technique.

Quantifying Asymmetry
The terms symmetry and asymmetry have been used interchangeably in the literature, with symmetry referring to the exact replication of one limb’s movement in that of the other. The term asymmetry therefore relates to the absence of symmetry.

Robinson et al. (1987) compared force values to determine the effects of chiropractic manipulation, and sought a dimensionless quantification of the difference between sides, which would allow symmetry of different variables to be compared. To achieve this quantification, Robinson et al. (1987) developed the SI, a ratio of left and right values, divided by a reference value, where a value of zero represents absolute symmetry:

$$SI = \left( \frac{\left( X_{left} - X_{right} \right)}{0.5 \left( X_{left} + X_{right} \right)} \right) \times 100\%$$  \[2.1\]

$SI = symmetry\ index$

$X_{left} = value\ for\ left\ side$

$X_{right} = value\ for\ right\ side$
Crenshaw and Richards (2006) proposed an alternative to the SI that did not contain the reported limitations of the SI, such as the low sensitivity and the potential for hugely inflated values. Their suggested method compared an entire waveform over a trial, calculating an overall asymmetry value. Whilst this may be of use for some variables, such as joint angle profiles, it is also necessary to be able to compare discreet data points, such as peak joint angles, identified in previous literature as being highly influential.

Zifchock et al. (2008b) addressed the inherent problems associated with the SI as a measure of asymmetry levels, such as the inconsistency in reference values that can be used (Herzog et al., 1989; Vagenas & Hoshizaki, 1992) and how the selection of mean reference values can drastically over-inflate reported findings, as shown by Herzog et al. (1989) who reported a SI value in excess of $13 \times 10^3$. Zifchock et al. (2008b) proposed another alternative to the SI which, unlike the method of Crenshaw and Richards (2006), can also be used to compare discreet values. They termed this new method the ‘symmetry angle’ ($\theta_{SYM}$). The $\theta_{SYM}$ is an arctan function of the ratio of two bilateral values, where a $\theta_{SYM}$ value of 0% indicates perfect symmetry and 100% indicates perfect asymmetry (Fig. 2.5).

Figure 2.5. Definition of the symmetry angle. Asymmetry is represented by any deviation ‘$\delta$’ from the ‘line of symmetry’ (adapted from Zifchock et al., 2008b).
Zifchock et al. (2008b) claimed that their new measure did not suffer from artificial inflation as could be the case with the SI and noted the advantage of a value that was truly limited to ±100%. Due to the inclusion of an arctan function in the calculation of the $\theta_{SYM}$, two equations were presented by Zifchock et al. (2008b) to ensure that values did not exceed 100%:

$$\theta_{SYM} = \frac{(45^\circ - \arctan(X_{left}/X_{right}))}{90^\circ} \times 100\%$$  \hspace{1cm} [2.2]$$

$\theta_{SYM}$ = symmetry angle
$X_{left}$ = value for left side
$X_{right}$ = value for right side

However, if:

$$\left(45^\circ - \arctan(X_{left}/X_{right})\right) > 90^\circ$$  \hspace{1cm} [2.3]$$

Then:

$$\theta_{SYM} = \frac{(45^\circ - \arctan(X_{left}/X_{right}) - 180^\circ)}{90^\circ} \times 100\%$$  \hspace{1cm} [2.4]$$

Zifchock et al. (2008a) highlighted some of the potential errors with the SI by comparing SI values using left and right leg values as reference values for SI calculation. They reported that across 52 participants, for a range of kinematic and kinetic variables, the majority of participants showed a difference of at least 15% when the opposing leg was used as the reference value. To validate the use of $\theta_{SYM}$ as a suitable alternative to SI, the authors assessed the correlation between $\theta_{SYM}$ and SI values, reporting perfect correlations ($r = 1.00$) for kinetic, structure and strength variables. Correlations for the two kinematic variables were lower initially ($r = 0.63$ and 0.58), however it was suggested by the authors that this was due to some extreme outliers caused by artificially inflated SI values, once these outliers were excluded from analysis the correlations increased to $r = 0.78$ and 0.94. It therefore seems reasonable to accept the use of $\theta_{SYM}$ as an alternative to SI and there are clear advantages to the use of this method.
Zifchock et al. (2006) investigated lower-limb asymmetry and injury potential, hypothesising that running asymmetry may predispose athletes to greater injury potential on one side. They recruited female runners, who ran at least 20 miles per week. Participants were grouped depending on whether they had suffered a unilateral tibial stress fracture. The study found that, whilst the athletes with an injury history displayed larger GRFs that the control group, asymmetry levels did not change significantly between groups. However, a large amount of within group variability was present in the level of asymmetry, with SI values ranging from 3.1 to 49.8%.

Following the development of the $\theta_{SYM}$ as an alternative to using the SI, Zifchock and Davis (2008) compared $\theta_{SYM}$ values for consecutive and non-consecutive footstrikes of 52 male and female runners. They compared both kinematic and kinetic data, reporting a mean difference of just 1.8% between $\theta_{SYM}$ calculated from consecutive and non-consecutive footstrikes. To justify the collection of non-consecutive footstrikes, the authors reported CV values both ‘between’ and ‘within’ sides. They found that for all variables measured, except for knee adduction, variability between sides was significantly greater than variability within sides. It was noted that the knee adduction results were due to three participants that displayed high levels of variability within a side and that excluding these data sets resulted in the knee adduction results following the same trend as the other variables. Zifchock and Davis (2008) concluded that it seemed acceptable to calculate asymmetry from non-consecutive footstrikes but that care should be taken when high levels of within-side variability are present. The consideration of intra-limb variability is an important feature that has been neglected in both the SI and $\theta_{SYM}$ measures of asymmetry. Intra-limb variability is an important function of asymmetry that should not be overlooked. Asymmetry can only be deemed to be present if the difference observed between limbs is larger than the difference within limbs (Giakas & Baltzopoulos, 1997b). Therefore, whilst the $\theta_{SYM}$ offers a robust method of quantifying the difference between contralateral limbs, results could be misleading if they are not combined with a suitable analysis of the differences present within limbs.
2.6.5 Summary
There are many different methods available for the collection and processing of kinematic and kinetic data. Recent technological advances have allowed the collection of very accurate kinematic data without the large processing time associated with traditional techniques. However, whilst contemporary methods of kinematic data collection are desirable due to their increased accuracy, traditional methods are still required for the non-intrusive collection of kinematic data. Collection of kinetic data can be achieved via the use of force plates, which do not interfere with athletes’ performance. However, it is also not possible to collect kinetic data during competition using this method due to the need to mount force plates underneath the running track. All of the data collection methods discussed in this section are susceptible to the introduction of noise within the collected data, which can lead to errors in the data. The effect of noise within data can be reduced by using a suitable filtering or smoothing method.

2.7 Chapter Summary
The literature reviewed in this chapter has offered insight into step characteristics as well as their kinematic and kinetic determinants. The work that has been done to date examining asymmetry in walking and running has shown that there is no overall consensus on gait asymmetry and highlights the need for further investigation into asymmetry, especially during sprint running. The analysis of asymmetry of unilateral amputee athletes has been discussed, along with the possible symmetry advantage experienced by bilateral amputees; however, the asymmetry of bilateral amputees and able-bodied sprinters has not yet been investigated. The methodological issues that have been reviewed have highlighted some of the issues that must be considered when collecting biomechanical data and the potential benefits and errors caused by assuming symmetry. The following three chapters use quantitative methods to address specific research questions relating to kinematic and kinetic asymmetry during sprint running. The final chapter then discusses the findings of each study and their implications on sprint running technique and data collection methodologies.
 CHAPTER 3 – DEVELOPMENT OF METHODS FOR THE ASSESSMENT OF STEP CHARACTERISTIC ASYMMETRY IN MAXIMAL VELOCITY SPRINT RUNNING

This chapter consists of two studies, one focussed on the development of methodologies for kinematic data collection, with the other applying these methods to the analysis of step characteristic asymmetry. The first study developed a field-based method for the collection of sprint data that could be used during training sessions and competition. The key pre-requisite of such a method was that it was non-intrusive to athletes so that it did not inhibit performance in any way. The second study then utilised the developed method for the analysis of step characteristic asymmetry in highly trained sprint athletes using data collected during training sessions.

There were two aims to the chapter; the first aim related to the first study and was to develop methods for the collection of kinematic sprint running data that can be used during specific data collection sessions and, non-invasively, during athlete’s training or competition. The second aim of this chapter concerned the second study and was to assess the amount of asymmetry present in step characteristics of two highly trained sprint runners.

3.1 Development of Kinematic Measurement Techniques

Study 1 has three themes that focus on the development of methods for the collection of sprint running data. The first concerns validation of the accuracy of an automated motion analysis system, to be used as a ‘gold standard’ with which to compare the alternative non-intrusive method. The second then compares the accuracy of an alternative non-intrusive method with the automated system. The final part of the study considers the calculation of CM when data is only available for a limited part of the body. The three themes are closely linked and shared similar data collection protocols. Therefore, the first study of this chapter is arranged so that introduction, methodology, results and discussion sections all contain a sub-section focussed on each of the three themes. The three themes are referred to in each section as follows:

1) Justification for the use of CODA automated system
2) Selection of alternative method for the collection of movement data
3) Calculation of horizontal velocity

3.1.1 Introduction

Justification for the use of CODA automated system
The accurate calculation of joint centre and other physiological landmark locations is paramount to the analysis of certain kinematic and kinetic variables in sprinting (Robertson et al., 2004). The advancement of automated motion analysis systems in the past few decades has enabled very accurate tracking of body landmarks, with reported position resolutions in the order of 5 to $10 \times 10^{-5}$ m (CODA, Charnwood Dynamics, Leicester; Richards, 1999). This level of resolution surpasses those reported in previous studies of sprint running (Bezodis et al., 2008; Bushnell & Hunter, 2007; Hunter et al., 2004b); however, spatial coordinate data may include errors caused by alignment of the system and environmental factors, such as lighting. Therefore, for CODA (Charnwood Dynamics, Leicester) to be accepted as the ‘gold standard’ with which to compare other methods of data collection, it was necessary to quantify the accuracy of the system and user for the collection of kinematic data. It was important to check that the accuracy of the system remained sufficiently high during the type of movements that will occur during data collections. A difficulty associated with the use of automated motion analysis systems is the occlusion of markers, which can occur when a scanner’s line of sight to a marker becomes obstructed by an athlete’s body or clothing. In the event of markers being occluded for small periods it is possible to interpolate the positional data for that marker and predict the marker’s location during the period of missing data; the use of this method could however, provide another source of error.

Selection of alternative method for the collection of movement data
Whilst the use of automated systems for the collection of kinematic data offers great accuracy (Richards, 1999), their use is restricted in some situations due to the intrusive nature of the systems, which require markers to be placed on athletes. The need to place markers on athletes limits the use of automated systems for the collection of data from athletes’ training. In longitudinal studies requiring extended periods of data collection, over months of training for example,
many athletes are reluctant to wear markers, due to perceived negative effects on performance. Some athletes have commented that, whilst wearing markers, they are conscious of trying not to displace them. If markers are displaced they can fall off the athlete, which interrupts the data collection and can interfere with the training session. Another limitation of the use of automated systems is that, at present, it is not possible to use them for the collection of competitive data due to the need for scanners to be positioned around the competitive environment.

For situations when it is not possible to place markers on athletes or position CODA scanners around the data collection volume, another method must be employed. One alternative method for the collection of spatial data is the use of video cameras to capture images of performance, which can be post-event processed using direct linear transformation (DLT) (Abdel-Aziz & Karara, 1971). Whilst the reported resolution of video-based DLT, approximately $2.5 \times 10^{-3} \text{ m}$ (Kerwin, 1995), is not as high as that of automated systems, it is still sufficiently high to be of use when collecting kinematic data for the analysis of sprint running and has been used previously for such analyses (Bezodis et al., 2008). Since DLT reconstructs digitised video images to calculate spatial coordinates of body landmarks, the only equipment required at the time of data collection are video cameras (and associated peripherals such as tapes etc.) and a calibration object, such as a rigid pole, of which video images are captured; therefore the cost associated with video-based data collection is much less than with automated systems. Video cameras can also be positioned further from the activity being recorded than the scanners used for automated motion analysis. The greater freedom offered during data collection has enabled the use of video to capture data from elite competitive events such as the Olympic Games (Exell et al., 2007; Mann & Herman, 1985).

DLT can be used to reconstruct video images in either two dimensions (2D-DLT) or three dimensions (3D-DLT). The main drawback to 3D-DLT is the high time demand associated with the digitising process. 2D-DLT (Walton, 1981) is a much less time demanding process than 3D-DLT, as it only requires video images from one camera view to be digitised, reducing the amount of digitising by approximately a half. There is also no need to synchronise images from multiple cameras, further reducing time demands. There is more post-event processing
required when a video based method of data collection is employed instead of an automated motion analysis system; however, the impact on the athlete during data collection is reduced as there is no need to place markers to the athlete. Collecting 2D data is logistically favourable, as only one camera is used and collection of calibration images can be performed faster, impacting less on the event, which is of great importance when collecting competitive data. The potential weakness of using 2D-DLT as opposed to 3D-DLT is that data points are projected onto one plane; this means that any out of plane movements are discounted and can translate to errors in the calculated location of data points in the calibrated plane. Therefore, 2D video based analysis is most suited to planar activities. Johnson and Buckley (2001) suggested that 2D methods are adequate for the analysis of sprint running, due to the movements predominantly occurring in the sagittal plane. In straight line sprint running, lateral movements are also restricted to some extent by the rules requiring athletes to stay in their lane during the race. As there are advantages and disadvantages to both 2D-DLT and 3D-DLT, it was necessary to quantify the error of the two systems when compared to CODA so that an informed decision could be made on which is the best method to use during future data collections when it is not possible to use an automated system. Furthermore, the ideal situation for reducing the environmental impact on athletes would be to have cameras located on the viewing balcony rather than the track. The viewing balcony at the National Indoor Athletics Centre, Cardiff is raised approximately 3 m above the track surface. Therefore, positioning cameras on the viewing balcony increases the angle at which the camera intercepts the track. To determine the effect of collecting data from cameras located on the viewing balcony, 2D analysis was performed using cameras located both on the track and the balcony. As discussed in Chapter 2, 2D-DLT can be used to reconstruct coordinates in both the running-plane and track-plane. 2D reconstruction was performed in both planes to allow a direct comparison of the two planes for the calculation of SL.

Calculation of horizontal velocity
The final part of the methodological section concerns the processing of data to calculate horizontal velocity. The fundamental performance criterion in sprint running is horizontal velocity, or the ability of the athlete to move their CM from the start line to the finish line in the shortest time. Due to the cyclic nature of the limbs during running and the effects of ground contacts on the movement of other body
landmarks, CM velocity is often used to represent the velocity of athletes (Arampatzis et al., 1999; Bezodis et al., 2008; Hunter et al., 2004a; Mero & Komi, 1985) as the impact of individual limb and segment movements is minimised by the inclusion of the rest of the body in the calculation.

As discussed in Chapter 2, there are instances when it is not possible to collect full kinematic data from both sides of an athlete’s body. Unilateral data collection can occur when using automated or manual methods of data collection; for example, when CODA scanners are aligned along one side of the track to maximise the section of a run that can be analysed (e.g. Gittoes & Wilson, 2010), or when only one side of the body is visible from video footage. When using some automated systems, the number of markers that can be used to collect data is limited. For example, when the CODA system is operating at 200 Hz, the number of markers is limited to 28. When kinematic data are only available for one side of the body or the number or position of markers is limited, it is important to still be able to accurately calculate the athlete’s mean horizontal velocity, so that comparisons can be made with other trials. As the left and right sides of the body cover a similar antero–posterior distance during a complete stride, the stride velocity of one side of the body should be similar to that of the contralateral side. It is necessary to quantify the accuracy of velocity when calculated using just one side of the body instead of both sides to ensure results are truly representative. Gullstrand et al. (2009) investigated the possibility of calculating vertical CM position during running with reduced numbers of markers. They reported that the difference between vertical displacement of the CM and the mid-point of two markers located either side of the sacrum was in the region of 0.001 m. Rabuffetti and Baroni (1999) recommended that the method used to calculate CM position should reflect the aim of the specific analysis. Later studies in this thesis are focussed on the kinematic and kinetic asymmetry of the lower limbs in sprint running; therefore, any influence of the upper body on the calculation of CM is unwanted. A method of measuring SV that uses markers located around the pelvis is desired. Furthermore, Forsell and Halvorsen (2009) noted that the large number of markers required to calculate CM location can lead to an increase in the number of rejected trials due to markers being dislodged and a reduction in ecological validity due to an increased interference with the athlete’s technique. Therefore, a method of calculating SV that uses minimal markers would be beneficial.
The purpose of the first section of this study was therefore to validate the accuracy of the CODA system so that it could be justified as the ‘gold standard’, with which to compare other non-intrusive data collection methods. The research question that emerged from this section of work was:

1. How accurate is the CODA system for the collection of spatio-temporal data during movements representative of sprint running?

The purpose of the second section of Study 1 was to assess which method of DLT would be the most suitable alternative method for use in the collection of kinematic data when it is not possible to use the CODA system. The following research question was devised:

2. Based on the error associated with each technique, is 2D-DLT or 3D-DLT most appropriate for the reconstruction of video-based sprint running data?

The purpose of the final section of the study was to assess the suitability of measuring horizontal velocity based on kinematic data from one side of the body and using markers located around the pelvis. The third research question that emerged was:

3. How accurate is the calculation of horizontal sprint velocity from the kinematics of one side of the body and from markers located around the pelvis?

3.1.2 Methods

3.1.2.1 Data Collection

*Justification for the use of CODA automated system*

Data collection for the study occurred in the National Indoor Athletics Centre, Cardiff. One CODA cx1 scanner (Charnwood Dynamics, Leicester) was utilised for data collection at a sampling rate of 800 Hz. The scanner was vertically mounted on a tripod so that its mid point was raised to a height of 1.30 m above the track surface. Two active CODA markers were attached to a rigid metal bar by means of adhesive tape. Initially three trials were collected whilst the bar was static, followed by three trials whilst the bar was moved in a ‘running action’ similar to the movement of an athlete’s shank during sprint running (shown in Fig. 3.1a). Three trials were collected whilst the bar was rotated in the sagittal plane facing the
CODA scanner; finally, three trials were collected whilst the bar was moved laterally (i.e. towards and away from the scanner). The running action was selected to represent the motion of an athlete’s leg whilst running, although it was not possible to move the bar at angular velocities that were representative of the movement; therefore, the rotating trials were used so that the markers were moved at speeds closer to those that would be experienced during sprint running. Following the rigid bar trials, five markers were placed at marked locations on a rigid metal plate (Fig. 3.1b). Three of the markers (A, B and C), when positioned on the plate, formed a ‘Pythagorean triple’ with sides of length 0.300, 0.400 and 0.500 m. The additional markers were positioned so that Marker D formed the rectangle ‘ABDC’ and Marker E was placed 0.300 m along the line ‘CB’, forming an obtuse angle ‘AED’. A range of angles were formed to represent the range of angles seen during sprint running, the minimum and maximum angles used in this study of 37 and 158° compare closely to the range reported by Mann and Herman (1985) for minimum and TO angles at the knee (35 and 158°). Data were captured whilst the plate was static, being moved along a lane without rotating and whilst being rotated.

Figure 3.1. Representation of the ‘running’ action performed with the rigid bar (a) and location of CODA markers on the rigid plate (b).

---

(a) marker

(b) marker

AC = 0.30 m
AB = 0.40 m
BC = 0.50 m
CE = 0.30 m

ABC = 37°
CAB = 90°
ACB = 53°
AED = 158°
Selection of alternative method for the collection of movement data

One male athlete volunteered for the study (age 21 years, height 1.84 m, mass 80.5 kg). The athlete was well trained and competed on a regular basis (100 m personal best 10.90 s). Data collection was centred 30 m from the start line. The CODA system (Charnwood Dynamics, Leicester), was utilised for data collection with two scanners (cx1) set at a sampling rate of 200 Hz. The scanners were vertically mounted on tripods (SLIK, Pro 700DX) so that the mid points of the scanners were raised to a height of 1.30 m above the track surface. Scanners were positioned on opposite sides of the track at a separation of 9.20 m (Fig. 3.2).

Figure 3.2. Location of CODA scanners used for comparison of CODA and video-based data collection, showing approximate field of view of each scanner (shaded area).

The setup provided the largest bilateral field of view along one lane of the track with two scanners (approximately 5.10 m). The field of view of the CODA system was centred on the 30 m mark. The CODA system was aligned using three cx1 markers positioned on the track surface, which determined the origin, sagittal and frontal planes. The cable connecting scanner two, located on the far side of the track, to the CODA hub was suspended at a height of 2.67 m above the track to allow the athlete to run underneath without having to alter their stride pattern (Fig. 3.3). Seventeen active CODA markers (cx1) were connected to nine twin-marker drive boxes. The markers and drive boxes were secured to the athlete using
double-sided tape and reinforced using PVC insulating tape. Markers were placed superior to the first inter-phalangeal joint of the second toe, lateral to the distal end of the fifth toe, the lateral side of the ankle, knee, hip, shoulder, elbow and wrist for both sides of the body, with the final marker placed on the athlete’s forehead.

Figure 3.3. The data collection area, showing the athlete passing underneath the raised CODA cables

Two 50 Hz video cameras (Sony, HVR-A1E) were mounted on tripods with their lenses raised to a height of 1.30 m above the track surface. These cameras (Cameras A and B) were positioned 13.86 m from the CODA origin so that they intercepted at an angle of 90°. Cameras A and B collected images for reconstruction via 3D-DLT.

Camera C (Sony, HVR-Z1E) was mounted on a tripod with the lens raised to a height of 1.30 m and positioned 9.80 m from the CODA origin for the collection of track level images for 2D-DLT. A final 50 Hz video camera (Sony, HVR-Z1E, Camera D) was mounted on a large tripod so that the lens was at a height of 2.50 m above the track surface and located 7.38 m from the CODA origin. Camera D had an angle of interception of 18.7° with the track, which is the smallest angle that would be encountered when filming the far lane from the viewing balcony.
Following the first four trials, Camera D was repositioned so that the lens was raised to a height of 2.80 m and a horizontal distance of 3.93 m from the CODA origin. This position simulated the greatest angle of interception of 35.5°, which would occur when filming an athlete in the near lane from the viewing balcony. Camera D collected images for 2D-DLT at a greater angle of interception with the track than Camera C to allow comparison between the two locations. All cameras recorded onto DVCAM tape (Sony, PDVM-40ME), with a shutter speed of 1/600 s and a fully open iris (f1.6). Cameras were zoomed so that the field of view covered a 6.00 m distance along the track, centred on the CODA origin. All cameras were manually focussed and then locked so that settings could not be altered during data collection. In order to calibrate video images, nine locations were marked on the track surface using masking tape. Three calibration marks were positioned on the inside edge of each of the two lane lines, with the remaining three positioned along the midpoint of the lane, the markers were located 2.00 m before, level with and 2.00 m after the CODA origin (Fig. 3.4).

![Diagram](image_url)

**Figure 3.4.** Location of calibration markers (grey) and video cameras (\(^\text{a} =\) Camera D initial position, \(^\text{b} =\) Camera D position for final 4 trials) relative to track lane lines (black).

Before the trials were completed, a vertical calibration pole was positioned at each marked location in turn. Three white calibration spheres were attached to the pole,
measuring 0.09 m in diameter and located at heights of 0.09 m, 1.17 m and 2.15 m. Video footage was collected by Cameras A and B when the pole was position on the six lane-line markers and by Cameras C and D when located on the three central markers. Footage was also captured by Cameras C and D of the track surface markers without the pole, to allow calibration in the track-plane.

To test the accuracy of the digitising process, 16 extra track markers were positioned along the diagonals between the four corner calibration markers (Fig. 3.5), the location of each of the extra markers was measured and video footage of them was collected. Footage of the track calibration markers and the calibration pole located on the mid lane markers was re-captured by Camera D following data collection, to allow calibration of the camera for the two different positions used.

![Figure 3.5](image_url) Location of additional markers used to test digitising accuracy (black) and calibration markers located on the track plane (grey). The top and bottom horizontal black lines define the running lane.

Prior to testing, the athlete completed their own warm up under their coach’s guidance. Video images and CODA data were then collected of eight maximal velocity trials. For each trial the athlete was instructed when to start and then to run with maximal effort to a finish line located 10 m past the data collection volume. The finish line was located past the data collection volume to stop the athlete decelerating during the data capture volume in anticipation of the finish line. Trials were rejected if any markers were dislodged or if the athlete noticeably altered their step pattern during the data capture volume; this was noted by the coach who observed all trials.

*Calculation of horizontal velocity*

Data collection was centred on the 30 m mark of the 120 m straight. The CODA system (Charnwood Dynamics, Leicester) was set up to run two scanners (cx1)
sampling at 200 Hz, as detailed in the previous section. 26 active CODA markers (cx-markers) were connected to twin-marker drive boxes. Markers were placed on the athlete superior to the first inter-phalangeal joint of the second toe, lateral to the distal end of the fifth toe, the lateral side of the ankle, knee, shoulder, elbow and third finger, the medial and lateral sides of the wrist, and anterior and posterior positions of the hip and head for both sides of the body.

The athlete was instructed to run with maximal effort to a finish line located 40 m from the start. CODA marker positional data were collected as the athlete ran through the data capture volume. Following each trial, an immediate visual check of the CODA data was performed to determine the inclusion or rejection of the trial based on marker visibility throughout the trial. Trials were rejected when markers were dislodged or if the athlete altered their stride pattern during the data collection volume.

3.1.2.2 Data Processing

*Justification for the use of CODA automated system*

The CODA software was used to calculate the separation of the markers when fixed to the rigid bar. Marker separation data was imported into spreadsheet software (Microsoft Excel, USA), which was used for subsequent calculations. Mean, maximum and minimum marker separation values were calculated, as well as standard deviation (SD) and coefficient of variation (CV) for all trials.

\[
CV = \frac{\sigma}{\mu} \tag{3.1}
\]

*CV = coefficient of variation*

*\(\sigma = \text{standard deviation}\)*

*\(\mu = \text{mean}\)*

The CODA software recorded the visibility of all markers during data collection; this record was used to determine the inclusion or rejection of trials. In the final trial, where marker visibility was lost for a section of the data capture, the data interpolation function in the CODA software was used to calculate the missing data points. The effect of interpolating the section of missing data was measured by
calculating CV for this trial both including and excluding the interpolated data points. CV values were expressed as a percentage of the mean value for each trial. To allow comparison between interpolated and measured marker positions for the same data points, a section of the final trial lasting for 1.40 s was selected for further analysis. Data for the final trial were duplicated and two sections of the duplicated data set, lasting for 0.40 and 0.20 s, respectively, were deleted. The CODA software was then used to calculate the missing data points using the interpolation function. For the angular accuracy check, the CODA software was used to calculate marker positions, marker separations and vector angles. The marker separation values were used to check against the measured locations of the markers. Root mean squared difference (RMSD) was calculated for each trial between vector angles measured using CODA and those calculated using trigonometry for the known ‘Pythagorean triple’ and the additional obtuse angle.

\[
RMSD = \left( \frac{1}{n} \sum_{i=1}^{n} (x_1 - x_2)^2 \right)^{1/2} \tag{3.2}
\]

\[RMSD = \text{root mean squared difference}\]
\[x_1 = \text{variable ‘1’}\]
\[x_2 = \text{variable ‘2’}\]

Selection of alternative method for the collection of movement data

Video data were digitised at 50 Hz using Peak MOTUS version 9.0 (VICON Peak, USA). Calibration points were digitised ten times each to reduce the effect of digitising error. Calibration points consisted of the spheres located on the calibration pole when situated at each marked position on the track surface and also the nine marked locations of the track surface, used for 2D-DLT reconstruction in the track plane. The anatomical locations of the CODA markers on the athlete, described in Section 3.1.2.1, were digitised for each camera view for every trial.

Digitised calibration and trial coordinates were imported into Target (Kerwin, 1995) for reconstruction using either 2D-DLT or 3D-DLT with lens correction. Positional data were filtered using a low-pass Butterworth digital filter; with the optimal cut off
frequency (9 Hz) determined using Winter’s (2009) residual analysis. Reconstructed coordinates were exported into CODA for the calculation of joint vector angles. The CODA software was used to calculate joint angles for both digitised data and data collected using the CODA system. To allow comparison between the different methods, all joint angles were calculated in the sagittal plane. Instants of TD and TO for the digitised data were detected visually from the video images. For the CODA data these occurrences were detected using the method of Bezodis et al. (2007) where TD and TO were defined using the occurrences of peak vertical acceleration of the foot markers. SL values were defined as the horizontal vector displacement in the sagittal plane of the tip of the toe, from TD of one foot to the subsequent TD of the contralateral foot. All calculations were performed in Microsoft Excel (Microsoft Excel, USA).

Digitising accuracy was measured using the 16 additional markers placed on the track. These markers were digitised from Camera D and their locations then reconstructed using 2D-DLT with lens correction. The calculated locations of the markers were compared to the measured locations, which were sited using a measuring tape with precision of 0.001 m. Objectivity of the digitising process was quantified by having another experienced digitiser re-digitise one of the trials. The location of the athlete’s CM was calculated from both data sets, as described in the subsequent section, and its location throughout the trial was compared.

Errors in SL and joint angle calculations for both methods of DLT were determined by calculating the RMSD between the digitised results and those calculated using CODA. RMSD values for each trial were then averaged to give a measure of the mean error for each camera view.

Calculation of horizontal velocity
Whole body CM position was calculated using the inertia parameters of de Leva (1996) with the exception of the foot segment, for which Dempster’s (1955) model was used. An additional 0.20 kg was added to the foot segment to account for the mass of a running spike, as recommended by Hunter et al. (2004a). Pseudo left and right CM positions were also calculated using the markers from just the left and right sides of the body, with the segment weightings doubled. For situations where the effects of the upper body on CM calculation are undesirable, the mid-
point of the iliac crest markers was also calculated. Horizontal velocity data were
calculated for the three CM locations for one complete stride cycle (left TD to
subsequent left TD), with instants of TD determined using the vertical acceleration
method of Bezodis et al. (2007). Step and stride velocity values were exported into
Microsoft Excel (Microsoft Excel, USA), which was used for subsequent
calculations. Mean CM velocity values were calculated for the duration of each
step and the differences between horizontal velocities of the CM, the pseudo left
and right CM’s (CM_{LEFT} and CM_{RIGHT}) and the mid-iliac crests were calculated.

3.1.3 Results

*Justification for the use of CODA automated system*

Table 3.1 shows marker separation values calculated by the CODA system for
trials when two markers were attached to the rigid bar. The separation between
the markers was within 0.001 m of the measured value of 1.302 m for static and
rotating trials. The difference increased to 0.002 m during ‘striding’ and lateral
trials. Markers were visible throughout the duration of the first four trials; however,
one of the markers was occluded for part of the final trial. To quantify the effect of
losing marker visibility, results are presented from the final trial both including and
omitting the interpolated sections of data when marker visibility was lost.

Table 3.1. Mean [±SD] marker separation and coefficient of variation values for
each trial type when the markers were attached to the rod.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Measured Separation (m)</th>
<th>Marker Separation (m)</th>
<th>CV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>1.302</td>
<td>1.303 [0.0001]</td>
<td>0.01</td>
</tr>
<tr>
<td>‘Running-action’</td>
<td>1.302</td>
<td>1.300 [0.0011]</td>
<td>0.08</td>
</tr>
<tr>
<td>Rotating</td>
<td>1.302</td>
<td>1.301 [0.0006]</td>
<td>0.05</td>
</tr>
<tr>
<td>Lateral*</td>
<td>1.302</td>
<td>1.300 [0.0015]</td>
<td>0.11</td>
</tr>
<tr>
<td>Lateral**</td>
<td>1.302</td>
<td>1.300 [0.0030]</td>
<td>0.23</td>
</tr>
</tbody>
</table>

*interpolated data points removed, **interpolated data points included

The coefficient of variation of the marker separation throughout the trials ranged
from 0.01% for the static trials to 0.23% for the lateral trial that included the
interpolated positional data. Figure 3.6 graphically demonstrates the effect of
missing data points and compares the marker separation values for the final trial including and excluding the sections of interpolated data.

Figure 3.6. Example results from one rotating trial identifying effects of interpolating missing data points (a) and discounting sections of data when markers became occluded (b).

For the angular accuracy check, the marker separation values were within 0.0001 m of the measured values. This magnitude of error meant that the angles calculated via trigonometry contained a maximum error of 0.02°. Table 3.2 shows the results of the comparison between the calculated values to those measured using the CODA system. Throughout all trials, all the measured angles were within 1° of the calculated values. SD was smallest for the static trials and largest for the rotating trials.

Table 3.2. Mean [±SD] vector angles for each trial type when the markers were attached to the plate.

<table>
<thead>
<tr>
<th>Angle</th>
<th>Calculated Angle (°)</th>
<th>Measured Angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Static</td>
<td>Rotating</td>
</tr>
<tr>
<td>&quot;ABC&quot;</td>
<td>37 [0.04]</td>
<td>36.87 [0.53]</td>
</tr>
<tr>
<td>&quot;ACB&quot;</td>
<td>53 [0.06]</td>
<td>52.87 [0.04]</td>
</tr>
<tr>
<td>&quot;BAC&quot;</td>
<td>90 [0.05]</td>
<td>89.73 [0.82]</td>
</tr>
<tr>
<td>&quot;AED&quot;</td>
<td>158 [0.16]</td>
<td>157.21 [0.40]</td>
</tr>
</tbody>
</table>

Figure 3.7 demonstrates the error when estimating missing data points through interpolation. The magnitude of error varied depending on the pattern of the original data, with the largest error occurring in the first section of interpolation for
data in the y axis due to the change in direction of the original waveform during the interpolated section.

Figure 3.7. Errors in interpolated positional data, solid lines show the original data set of a marker's x, y and z positions relative to the CODA origin, whilst the broken lines show the estimated positions produced from the interpolation function.

Selection of alternative method for the collection of movement data

2D mean digitiser error between the measured locations of the track marks and the locations calculated from video data is presented in Table 3.3. The mean error was calculated as 0.0041 m when comparing the digitised locations of the extra track markers with their measured locations. The mean error was three times larger in the x direction (perpendicular to the lane lines) than the y direction (parallel to the lane lines). Full results of the digitising accuracy check are presented in Appendix A.1.

Table 3.3. Mean [±SD] results of the digitising accuracy check, the x direction is lateral across the lane, the y direction is parallel to the lane lines.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Mean Error (m)</th>
<th>Maximum Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>0.006 [0.003]</td>
<td>0.011</td>
</tr>
<tr>
<td>y</td>
<td>0.002 [0.002]</td>
<td>0.007</td>
</tr>
<tr>
<td>Mean</td>
<td>0.004 [0.003]</td>
<td>0.011</td>
</tr>
</tbody>
</table>
SL results comparing data calculated from video data and CODA are presented in Table 3.4. Results showed that 3D-DLT could be used to calculate SL values similar to those calculated using CODA, with the average SL difference less than 0.5% (0.006 m). The next smallest difference was for data collected from Camera D when reconstructed in the track plane, with an average difference of 0.8% (0.01 m). The most error for the calculation of SL was found in the values calculated from 2D-DLT cameras when reconstructed in the running plane; on average these results differed by approximately 2.25% (0.041 m).

Table 3.4. Mean [±SD] differences in SL between values calculated using CODA and those calculated from DLT.

<table>
<thead>
<tr>
<th>DLT Method</th>
<th>Camera Location</th>
<th>Mean SL Difference (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D running-plane</td>
<td>Balcony*</td>
<td>0.020 [0.012]</td>
</tr>
<tr>
<td></td>
<td>Balcony**</td>
<td>0.058 [0.027]</td>
</tr>
<tr>
<td></td>
<td>Track</td>
<td>0.045 [0.027]</td>
</tr>
<tr>
<td></td>
<td>Balcony*</td>
<td>0.010 [0.003]</td>
</tr>
<tr>
<td>2D track-plane</td>
<td>Balcony**</td>
<td>0.021 [0.010]</td>
</tr>
<tr>
<td></td>
<td>Track</td>
<td>0.021 [0.033]</td>
</tr>
<tr>
<td>3D</td>
<td>Track</td>
<td>0.006 [0.003]</td>
</tr>
</tbody>
</table>

*shallow viewing angle, **steep viewing angle.

Differences between joint angles calculated from CODA data and data calculated from video-based methods are presented in Table 3.5. 3D-DLT contained the least difference with next least difference being for 2D-DLT using Camera C.

Table 3.5. Mean [±SD] RMSD between joint angles calculated from CODA data and those calculated from DLT.

<table>
<thead>
<tr>
<th>DLT Method</th>
<th>Camera Location</th>
<th>Mean Error (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ankle</td>
</tr>
<tr>
<td>3D</td>
<td>Track</td>
<td>3.96 [2.01]</td>
</tr>
</tbody>
</table>

*shallow viewing angle, **steep viewing angle.
Calculation of horizontal velocity

Figure 3.8 shows example velocity profiles of the four calculated horizontal velocities over one complete stride for one trial. Results are presented as a percentage of one stride from TD of one foot to the subsequent TD of the same foot. There is a cyclical over and under-estimation of CM velocity when using $\text{CM}_{\text{LEFT}}$ and $\text{CM}_{\text{RIGHT}}$ (Fig. 3.8a). Mean stride velocities for the CM, $\text{CM}_{\text{LEFT}}$ and $\text{CM}_{\text{RIGHT}}$ for all strides were 8.21, 8.20 and 8.22 m·s$^{-1}$, respectively, equating to percentage errors of 0.12% when using the left or right CM instead of the true CM. However, when velocity was compared for individual steps between CM, $\text{CM}_{\text{LEFT}}$ and $\text{CM}_{\text{RIGHT}}$, the latter two resulted in mean differences with CM velocity of 0.10±0.06 m·s$^{-1}$. The mean difference between CM and iliac$\text{MID}$ velocity was 0.00±0.02 m·s$^{-1}$ over both a complete step and stride cycle.

Figure 3.8. Example data of one trial comparing velocity of CM with $\text{CM}_{\text{LEFT}}$ and $\text{CM}_{\text{RIGHT}}$ (a) and iliac$\text{MID}$ (b) over a complete stride from TD of one foot to subsequent TD of same foot.

3.1.4 Discussion

Justification for the use of CODA automated system

The purpose of the first section of the study was to validate the accuracy of the CODA system for the collection of spatio-temporal data during movements representative of sprint running. Marker separation results reinforced the reported high accuracy levels of the CODA motion analysis system (Richards, 1999), showing errors in the region of 0.1% for the measured length of a rigid bar. Angular results were within 1° of the calculated values of known angles throughout all trials, showing that the accuracy of the CODA system remains high for the calculation of joint angles during movements that are representative of running. A
comparison of different automated systems performed by Richards (1999) found that six other systems tested produced accuracy results similar to, or better than, those obtained using the CODA system for the calculation of marker separation and a measured angle. The high accuracy of CODA and other automated systems confirms the selection of automated systems as the gold standard for collecting kinematic data. CV values for the measured marker separation during both static trials and movements similar to those made by athletes’ limbs during running were very low indicating that the system’s accuracy remains high during running movements.

The potential negative effects of interpolation highlighted the great importance of marker visibility during data collections. Use of the interpolation function in the CODA software led to CV results more than doubling. Figure 3.5 demonstrated the possible anomalous nature of interpolated results compared with original data points. The potential error of interpolated data is further represented by Figure 3.6, which demonstrated how sudden changes in the movement pattern of a marker (such as that of the y coordinate between 3.4 and 3.8 s) can be excluded if a fitting technique has to be employed. The possibility of markers being obscured is a drawback to automated systems and marker visibility can be problematic during the analysis of certain movements. The error seen in the interpolated positional data highlights the need to ensure that marker visibility is maximised during data collection to reduce anomalous data. The interpolated results showed the potential for misleading data if an athlete changes their direction of movement whilst a marker is obscured.

**Selection of alternative method for the collection of movement data**

The mean error reported in the digitising accuracy test was higher than the theoretical resolution of 0.0025 m reported by Kerwin (1995). The mean error result of 0.0041 m reduced to 0.0020 m in the direction that SL is measured. If this amount of error were included in both foot contacts of a step, the SL error would still be <0.01 m, which is the precision reported in previous studies of sprint running (Bezodis et al., 2008; Bushnell & Hunter, 2007; Hunter et al., 2004b).

When comparing the digitised measures of SL to those collected using CODA, the largest SL error occurred in 2D trials reconstructed in the running plane. A visual
comparison of the recorded images revealed that the trials containing the most error (in excess of 0.10 m) were those where TD occurred towards the lane lines. The sections of the lane closest to the lane lines were the furthest from the central calibrated plane and, therefore, contained the most out of plane error. However, 2D SL results when reconstructed in the track plane contained error of <0.01 m. The best results for the calculation of SL using 2D-DLT were from the balcony camera when at the lower position, resulting in approximately half the error of the other two camera positions. The accuracy of ~0.01 m is similar to that obtained by Bezodis (2006) for calculation of SL.

The calculation of joint angles was typically more error prone than other variables such as SL due to the inclusion of a third marker in the calculation. 3D-DLT calculated joints angles with mean differences of <4.5° compared to CODA. The next most accurate method was 2D-DLT using Camera C where the largest mean error increased to 5.56° for the calculation of the ankle angle. The results calculated from the balcony cameras contained the most error, with high error values reported in the results for Camera D when in the second position, which gave the largest angle of interception with the track. The tendency for errors to be larger when the angle of interception with the track increased was due to out of plane errors having a greater effect when the camera is not positioned perpendicular to a movement. Irwin and Kerwin (2001) reported more favourable angular results when using 2D-DLT, with mean hip and shoulder errors of approximately 2.86 and 3.44°, respectively.

Calculation of horizontal velocity
There was close agreement between average stride velocity values calculated using CM, CM_{LEFT} and CM_{RIGHT}. CM velocities calculated from just one side of the body were found to produce an acceptable representation of horizontal velocity over a complete stride. There were sections of the stride when each side over estimated velocity, followed by a section where it was under estimated. The cyclical over and under-estimation of velocity was due to movements of the athlete being out of phase so that one side slows down relative to the other as it contacts the floor and then swings forward, reversing the effect during the contact phase of the opposite leg. The differences in CM_{LEFT} and CM_{RIGHT} velocity at different parts of the stride indicated that this method may not be suitable for use when analysing
movements that are not complete strides. For example, if a single step were to be analysed using velocity calculated from one side of the body, there could be an over or under estimation (as high as 5% for this data set). Comparing CM velocity with velocity calculated using the mid-point of markers located in the iliac crests showed that there is close agreement between the two measures with mean step and stride velocity differences being 0.00±0.02 m∙s\(^{-1}\). The inclusion of markers located on both sides of the body means that velocity calculated using markers located on the iliac crests is accurate over a step cycle, whereas when using markers located on one side of the body, analysis of less than a full stride could lead to over or under-estimation of CM velocity.

### 3.1.5 Conclusion

The analyses performed in this study have been instrumental in deciding the methodologies to be used in future studies of the thesis. The first part of the study reinforced the accuracy levels that automated systems are able to measure spatial locations to. It also highlighted the need for high marker visibility and indicated the error that can be induced by poor marker visibility.

The second part of the study quantified the errors that can occur when using manual motion analysis techniques instead of automated systems and the extra error associated with the use of 2D analysis instead of 3D. The error included in 2D methods can be reduced by mounting the cameras at varying heights. SL errors were minimised by using a camera that intercepted the track at approximately 20°, whilst errors in joint angle calculation were lowest using a camera positioned at a height level with the athlete. Using two cameras to satisfy the optimal conditions for calculating step characteristics and joint angles would be a less time consuming alternative to using 3D-DLT as digitising time would still be reduced and the camera views would not have to be time synchronised.

The final part of the study demonstrated the ability to accurately calculate SV for an athlete using a reduced marker set. The ability to accurately calculate SV from one side of the body is of great importance when data collections do not facilitate the collection of full body data. The study therefore indicated the extent of the error that could be introduced by using \(\text{CM_{LEFT}}\) or \(\text{CM_{RIGHT}}\) to calculate velocity over less than a complete stride.
The introduction to this study posed three research questions relating to the development of methodologies for use in sprint running data collections. These questions are answered thus:

1. **How accurate is the CODA system for the collection of spatial data during movements representative of sprint running?**

   The CODA system was found to be capable of calculating marker separation values with errors of approximately 0.001 m, which were maintained whilst collecting marker location data during movement representative of an athlete’s lower limbs during sprint running. Angular values calculated from CODA markers located on a rigid plate were determined to within 1° of the known values.

2. **Based on the error associated with each technique, is 2D-DLT or 3D-DLT most appropriate for the reconstruction of sprint running data?**

   For SL measurement, 2D-DLT reconstructed in the track plane was found to offer the best compromise of reduced impact on the performance environment, data processing time and accuracy of measurements compared to 3D-DLT. SL results calculated using 2D-DLT were within 0.01 m of values calculated using the gold standard CODA system. For calculation of angular data during sprint running, 3D-DLT was found to contain the least error (~4°). 2D-DLT reconstructed in the running plane contained out-of-plane error which increased the mean error of lower-limb joint angles to ~5°. Therefore, 2D-DLT is acceptable as a less obtrusive alternative to CODA for the collection of SL data. However, for the calculation of joint angles, 2D-DLT included larger errors than 3D-DLT so the latter is recommended.

3. **How accurate is the calculation of horizontal sprint velocity from the kinematics of one side of the body and from markers located around the pelvis?**

   SV calculated over a complete stride was similar when calculated using markers from one or both sides of the body. Use of unilateral markers to calculated CM velocity over less than a stride could be error prone due to the different functions of the left and right sides during different phases of a stride. Step velocity was similar when calculated using the CM and the mid-
point of markers located on the iliac crests due to the inclusion of data collected from both sides of the athlete. Therefore, the use of velocity calculated using markers located on the iliac crests is recommended when analysing step data.

Based on the results of these methodological studies, decisions have been made as to the most suitable methods of data collection for use in the subsequent studies of this thesis. Wherever possible, the CODA system will be used. The accuracy of the CODA system is superior to the video-based methods available. There may be occasions when it will not be possible to use the CODA system, such as in training and competition. When this is the case, 2D-DLT will be utilised for the collection of SL data using a video camera raised to a height so that it intercepts the track at approximately 20°. When kinematic data for the analysis of joint angles is required 3D-DLT will be employed using two cameras positioned on the track. For situations where upper body movements are not of interest, it has been shown that SV calculated using the mid-point of markers located on the iliac crests provides comparable results to those of the CM, whilst not being influenced by the upper body.

3.2 Bilateral Asymmetry of Step Characteristics in Maximal Velocity Sprint Running

3.2.1 Introduction

The second study of this chapter applies some of the methods developed in the first study (Section 3.1) to analyse bilateral asymmetry of step characteristics. Chapter 2 discussed some of the key kinematic and kinetic areas that sprint running research has investigated and some of the major factors that have been identified as affecting performance. One area that has not been investigated in sprint running research is that of bilateral asymmetry. Asymmetry has important implications on injury predisposition, data collection and informing coaches (Karamanidis et al., 2003; Zifchock et al., 2006). Whilst previous research has investigated kinematic asymmetry of the lower limbs during submaximal running (Karamanidis et al., 2003; Vagenas & Hoshizaki, 1992), the author is not aware of any similar work on sprint running. Ciacci et al. (2010) stated that they checked for asymmetry prior to collecting data for their analysis of sprint running; however,
they did not report any asymmetry results relating to this. Information relating to
the amount of asymmetry present in step characteristics of sprint running could be
useful to coaches, highlighting potential technique or strength imbalances. From a
data collection perspective, information on step characteristic asymmetry could
influence the decision to analyse sprint running data on a step or stride basis. If
asymmetry between steps is low, it may be suitable to analyse complete strides;
however, if asymmetry is present in step characteristics, a step analysis may be
required so that the differences between left and right steps can be detected. The
lack of research into asymmetry of sprint running indicates that, in studies where
data has been collected from both sides of the body (Hunter et al., 2004a; 
Luhtanen & Komi, 1978; Mero & Komi, 1985) symmetry has either been assumed
or the possibility of asymmetry has not been considered within the study.

As discussed in Chapter 2, step characteristics are the key discrete kinematic
values related to successful sprinting. Since SV is the product of SL and SF, any
asymmetry present in the latter two could have implications on the performance
outcome. SL and SF have been identified as the highest order variables
influencing SV (Hay, 1994; Hunter et al., 2004a). Therefore, it is important to gain
an understanding of these fundamental variables before investigating the
underlying causes of them, the kinematic and kinetic variables related to sprint
running. The data for this comparison were collected using the most suitable
method selected from the methodological section of the study presented in Section
3.1, allowing a large amount of data to be collected for two athletes during regular
training, without impacting on the session. To allow asymmetry of step
characteristics to be calculated, SV was required rather than stride velocity.
Therefore, the unilateral method of calculating velocity described in Section 3.1.2.2
was not suitable for this study.

The aim of this analysis was to quantify the asymmetry of step characteristics for
two highly trained sprint runners. To achieve this aim the following research
questions emerged:

1. How asymmetrical are the step characteristics of contralateral steps during
maximal velocity sprint running?
2. What is the interaction of asymmetry in SV, SL and SF?
3. How similar are step characteristic asymmetries for different athletes?
It was hypothesised that there would be a small amount of asymmetry present in SV for athletes due to the constraint of having to stay within a running lane. It was also speculated that either SL or SF asymmetry would have a greater influence on SV asymmetry, based on which factor had a greater influence on SV.

3.2.2 Methods

3.2.2.1 Data Collection

Video images were collected during two identical training sessions completed on consecutive weeks. Two highly trained male athletes (100 m PBs 10.22 & 10.88 s) completed 16 repeat 60 m sprints in each session, under their coach’s guidance. Ethical approval was gained from the University Research Ethics Committee and both athletes gave written informed consent to participate in the study. An example participant information sheet and written informed consent form is contained in Appendix A.6. Data collection was centred 40 m from the start line. Athletes had 2.5 minutes rest following each run and an additional 8 minutes following every fourth run. The athletes and coach were not keen on the use of surface anatomical markers for this study as they felt that training would be interrupted in the event of markers being dislodged; therefore, a video based method of data collection was selected. Video data were collected using two video cameras (Sony, HVR-Z1E), one located on the viewing balcony at a height of 2.80 m, giving an angle of interception of 19° with the track surface. The second camera was located on the track at a height of 1.30 m and was used to calculate CM position. Both cameras captured images at 50 Hz with a shutter speed of 1/425 s and a fully open iris (f1.6). Prior to the session images of track-plane and running-plane calibration objects were captured, as in Section 3.1.2.1. Steps were accepted for analysis if the whole of the athlete was completely in view of the camera located on the track for the fields immediately before and after TD at the beginning and end of the step. In total 27 left-to-right (L-R) and 31 right-to-left (R-L) steps were collected for athlete ‘A’ and 14 L-R and 31 R-L steps for athlete ‘B’.

3.2.2.2 Data Processing

Video images were digitised using Peak MOTUS version 9.0 (VICON Peak, USA). For SL calculation, the toe of the contact foot was digitised three times during the frame immediately following TD and a mean value taken to reduce digitiser error.
A 17-point model was used for whole body digitisations comprising the top of head, tip of the left and right hands, left and right feet and joint centres of the left and right wrists, elbows, shoulders, hips, knees and ankles (Fig. 3.9).

Figure 3.9. Bilateral digitised anatomical locations used to calculate CM position at the point of TD. The position of Points 2 and 10 were used for SL calculation.

Digitised coordinate data were reconstructed using 2D-DLT with lens correction (Walton, 1981). Further processing was performed in MATLAB (R2009a, The MathWorks, USA) using program step_char (Appendix B). Positional coordinate data were filtered using a fourth order low-pass Butterworth filter. Cut-off frequencies were determined via the autocorrelation method described by Challis (1999) and implemented in program autocor_CO (Appendix B). Horizontal CM location was calculated using the 17-point model digitised locations taken from the track camera combined with the inertial parameters from de Leva (1996), apart from the foot segment, for which the inertial parameters from Dempster (1955) were used with the addition of the typical mass of a running shoe (0.20 kg), as recommended by Hunter et al. (2004a). Horizontal CM position was calculated for fields immediately before and after TD then a mean value was calculated from the two fields to estimate the CM position at the point of TD, as suggested by Bezodis (2006). CM displacement was calculated between consecutive TDs and divided by the change in time from the field directly before one TD to the field directly before the subsequent TD to give mean SV. Mean reconstructed values from the three
digitised toe locations from the balcony camera were used to calculate SL from the
TD of one foot to the subsequent TD of the contralateral foot. SF was
subsequently calculated by dividing SV by SL.

The $\theta_{SYM}$ was selected as the most appropriate method for quantifying asymmetry
based on the strengths discussed in Chapter 2 and the potential artificial inflation
associated with other methods such as the symmetry index (Herzog et al., 1989).
$\theta_{SYM}$ values were calculated using the method of Zifchock et al. (2008b),
presented in Equation 3.3:

$$\theta_{SYM} = \frac{45^\circ - \arctan(X_{\text{left}}/X_{\text{right}})}{90^\circ} \times 100\%$$  \[3.3\]

$\theta_{SYM} = \text{symmetry angle}$
$X_{\text{left}} = \text{mean value for the left side}$
$X_{\text{right}} = \text{mean value for the right side}$

A positive $\theta_{SYM}$ value indicated a larger L-R value than R-L and a negative value
indicated that R-L>L-R. Including the polarity of the $\theta_{SYM}$ values allowed the
interaction of step characteristic asymmetry to be determined. Using the method of
Zifchock et al. (2008b) $\theta_{SYM}$ values are normalised to percentage values; therefore
a value of 100% represents complete asymmetry where left and right values are
equal in magnitude but with opposite polarity. For values that display the same
polarity, $\theta_{SYM}$ values are limited to 50%, which occurs when one value approaches
zero.

Step characteristic results were tested for normality using the criteria presented by
Peat and Barton (2005). The first criterion of this method was that if the difference
between the mean and median was $\leq 10\%$ the data were accepted as normal. All
variables for both athletes met this first criterion; therefore parametric statistics
were utilised to test the significance of differences between contralateral steps.
Significant differences between L-R and R-L values for SV, SL and SF were
determined using a paired samples t-test with an alpha level of 0.05 (Vincent,
2005).
3.2.3 Results

Mean SV, SL and SF values for R-L and L-R steps are presented in Table 3.6 along with $\theta_{\text{SYM}}$ values for each variable. There were differences in mean velocity between the R-L and L-R steps of 0.13 m·s$^{-1}$ for Athlete A and 0.11 m·s$^{-1}$ for Athlete B. Differences in SV were due to differences in mean SL of 0.04 m and 0.02 m and changes in mean SF of 0.11 Hz and 0.09 Hz for Athletes A and B, respectively. Both athletes’ $\theta_{\text{SYM}}$ values displayed the same polarity for each variable, with positive $\theta_{\text{SYM}}$ values for SV and SF indicating that step R-L was less than step L-R, whilst the opposite was observed for SF. Despite both athletes displaying similar $\theta_{\text{SYM}}$ magnitudes, differences between R-L and L-R were significant for all three step characteristics for Athlete A, whereas none of the step characteristics displayed a significant difference between contralateral steps for Athlete B.

Table 3.6. Mean [±SD] SV, SL, SF and $\theta_{\text{SYM}}$ measures for contralateral steps for Athletes A and B.

<table>
<thead>
<tr>
<th>Athlete</th>
<th>Step</th>
<th>Step Velocity (m·s$^{-1}$)</th>
<th>Step Length (m)</th>
<th>Step Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>R-L</td>
<td>10.28 [0.15]*</td>
<td>2.41 [0.04]*</td>
<td>4.28 [0.09]*</td>
</tr>
<tr>
<td></td>
<td>L-R</td>
<td>10.41 [0.12]*</td>
<td>2.37 [0.03]*</td>
<td>4.39 [0.07]*</td>
</tr>
<tr>
<td></td>
<td>$\theta_{\text{SYM}}$</td>
<td>0.40%</td>
<td>-0.45%</td>
<td>0.83%</td>
</tr>
<tr>
<td>B</td>
<td>R-L</td>
<td>9.30 [0.14]</td>
<td>2.25 [0.03]</td>
<td>4.13 [0.09]</td>
</tr>
<tr>
<td></td>
<td>L-R</td>
<td>9.41 [0.13]</td>
<td>2.23 [0.03]</td>
<td>4.22 [0.11]</td>
</tr>
<tr>
<td></td>
<td>$\theta_{\text{SYM}}$</td>
<td>0.37%</td>
<td>-0.36%</td>
<td>0.73%</td>
</tr>
</tbody>
</table>

* = p<0.05 between R-L and L-R

Figure 3.10 shows changes in SV relative to changes in SL and SF for athletes A and B. Both athletes displayed a tendency for increases in SF to cause an increased SV. Changes in SL appeared more variable and did not display a clear relationship with SV for both athletes. The lack of relationship between SL and SV was particularly evident for Athlete B where the largest (2.32 m) and smallest (2.16 m) SL values both occurred with similar SV values of 9.51 and 9.52 m·s$^{-1}$, respectively.
Figure 3.11 includes mean step characteristic and \( \text{ABS}\theta_{\text{SYM}} \) results for both athletes. In both graphs the absolute \( \text{ABS}\theta_{\text{SYM}} \) is represented in the upper section, with the lower section showing mean R-L and L-R values for SV, SL and SF displayed as a percentage of the maximum value obtained by that athlete. Both athletes displayed the largest amount of asymmetry in SF. \( \theta_{\text{SYM}} \) polarity was different for SL and SF for both athletes, shown in the lower section of Figure 3.11 (i.e. for SL L-R<R-L but for SF R-L<L-R).
3.2.4 Discussion

The aim of this study was to quantify the asymmetry of step characteristics for two highly trained sprint runners. The methods developed in the first study of this chapter have been used to collect data during two highly trained athletes’ training sessions. A prerequisite of the method employed was that it did not interfere with the training session by hindering the movements or delaying the athletes. The use of a video-based analysis allowed data to be collected without the need to place any markers on the athletes or delay the training session.

Step characteristic asymmetry

The $\theta_{SYM}$ has been utilised in this study to quantify the asymmetry present in step characteristics for the athletes investigated. When separating steps into L-R and R-L, slight differences between the two sides were apparent. Athlete A showed a $\theta_{SYM}$ difference in mean velocity of 0.40%. Faster L-R steps were achieved with a greater SF equating to a $\theta_{SYM}$ value of 0.83%, which led to a reduction in SL where the $\theta_{SYM}$ was -0.45%. Athlete B also displayed a positive $\theta_{SYM}$ for velocity (0.37%), the SV asymmetry was the result of a larger L-R SF ($\theta_{SYM}$=0.73%) and a smaller L-R SL ($\theta_{SYM}$=-0.36%).

There was a slightly larger difference between R-L and L-R step velocity for Athlete A than for Athlete B, although both athletes displayed low levels of asymmetry with $\theta_{SYM}$ values less than 0.5%. Differences between R-L and L-R
steps were significant for all variables for Athlete A, whereas none were found to be significantly different for Athlete B. For both athletes L-R steps had a smaller mean SL and larger mean SF, indicating that on an intra-athlete level, SF may be the limiting factor on performance for these athletes.

From a data collection perspective, the significant differences observed between contralateral steps for Athlete A support the use of a step-based analysis as opposed to a stride-based analysis where possible. If only stride information was available for Athlete A, the significant differences in the step characteristics of each side would not be detectable.

**General observations**
Athlete A was consistently faster than Athlete B showing a mean velocity difference of 11% (10.34 compared with 9.34 m·s⁻¹). This greater velocity was due to a combination of 7% larger mean SL (2.39 compared with 2.24 m) and a 4% larger mean SF (4.33 compared with 4.16 Hz).

Comparing the values reported with those of previous studies highlights how different athletes can achieve similar SV using different SL and SF combinations. Athlete B achieved mean velocity and SF values (9.34 ms⁻¹ and 4.16 Hz) almost identical to those reported by Luhtanen and Komi (1978) of 9.30 m·s⁻¹ and 4.17 Hz; however, Mann and Herman (1985) reported a similar velocity of 9.29 m·s⁻¹ but with a 3% larger SL (2.31 m) and 4% smaller SF (4.01 Hz) than Athlete B. Similarly, Mann and Herman (1985) also reported step characteristics for a sprinter with a velocity similar to that of Athlete A (10.34 m·s⁻¹) but with a 4% larger SL (2.49 m) and a 4% smaller SF (4.17 Hz).

Analysing the intra-athlete differences in SV, SL and SF, suggests that both athletes’ velocities were more affected by SF than SL. The relationship appears stronger for Athlete B than for Athlete A. The difference in which factor greatest influences SV supports the findings of previous studies that have looked at intra-athlete differences approaching maximal velocity (Kuitunen et al., 2002; Luhtanen & Komi, 1978; Mero & Komi, 1985).
A further finding of the study was the consistency in foot placements, and therefore SL, of Athlete A compared to Athlete B. The greater consistency in foot placement of Athlete A is reflected in the fact that, of all trials completed, only five didn’t include two complete steps due to one of the foot contacts occurring outside of the field of view. For Athlete B however, there were fifteen trials during which either the first or last foot contact was either partially or fully outside the field of view.

### 3.2.5 Conclusion

The aim of this analysis was to quantify step characteristic asymmetry for two highly trained sprint runners. Step characteristic data collected on two experienced athletes during a formal training session demonstrated a small amount of asymmetry in CM velocity between L-R and R-L steps, which was explained by larger asymmetries in SL and SF that were opposite in direction as to which side displayed a larger value. Three research questions were devised in the introduction to this study, these are addressed as follows:

1. **How asymmetrical are the step characteristics of contralateral steps during maximal velocity sprint running?**
   
   As hypothesised, a small amount of asymmetry was found for step characteristics during maximal velocity sprint running, with all $\theta_{SYM}$ values being close to the value of 0%, which represents no asymmetry being present. The hypothesis of a small amount of asymmetry being present in SV was due to the requirement of athletes to stay within their running lane during a race, necessitating similarity in the output measure (SV) of each side. The small asymmetries that were present were largest for SF for both athletes, with similar amounts of asymmetry for SV and SL.

2. **What is the interaction of asymmetry in SV, SL and SF?**
   
   For both athletes, asymmetry was largest for SF than the other step characteristics. The direction of asymmetry was different for SF and SL for both athletes, which resulted in the smaller SL asymmetry having a reducing effect on the SV asymmetry. As hypothesised, the step
characteristic that had the largest effect of SV asymmetry (SF) was also the variable that had the largest effect on SV values over the training sessions.

3. How similar are step characteristic asymmetries for different athletes?
Asymmetry results displayed a similar pattern for both athletes, despite the difference in SV between the two athletes. Both athletes displayed a larger asymmetry for SF than for SL. The opposite direction of asymmetry for SL and SF meant that the smaller SL asymmetry negated some of the asymmetry present in SF, resulting in a smaller amount of asymmetry for SV than SF.

Step characteristic asymmetry was different for the two athletes investigated in this study. Athlete A displayed a significant difference between sides for all variables, whereas no significant differences were observed for Athlete B. The significant differences observed for Athlete A could have implications on data collection and analysis techniques, as it has proven that if data are not collected for both R-L and L-R steps for this athlete, results may not be representative of the movements of the athlete. SL and SF are the two variables that directly influence changes to SV. To gain further insight into the causes of the observed asymmetry in these factors and to assess the causes of the significant differences observed for step characteristics further analysis must be performed, investigating the asymmetry of the kinematics of sprint running.

3.3 Chapter Summary
This chapter has demonstrated the levels of accuracy that can be obtained for the collection of kinematic sprint running data in both a laboratory and field-based environment. Key issues that should be considered when implementing both manual and automated methods of motion analysis have been presented and supported. In the second study, the application of a non-intrusive video based method has been used to address the phenomenon of asymmetry in step characteristics. As hypothesised, the analysis of step characteristics demonstrated that there are low levels of asymmetry in step characteristics during maximal velocity sprinting; however, the differences between sides were significant for all variables for one of the athletes tested. For the two athletes tested in this study,
one exhibited significant asymmetry for all step characteristic variables, whilst the other athlete did not display significant asymmetry for any. The difference in significant asymmetry observed between the athletes indicates that asymmetry may vary on an inter-athlete basis and supports the need for individual analyses to be performed so that asymmetries are not masked by averaging multiple athletes' results. The significant difference observed in step characteristics indicates that asymmetry may be present in the underlying kinematic and kinetic variables that influence these step characteristics. The following chapters will consider the asymmetry of the kinematic and kinetic factors that influence step characteristics.
CHAPTER 4 – KINEMATIC ASYMMETRY OF MAXIMAL VELOCITY PHASE 
SPRINT RUNNING

4.1 Introduction

Chapter 3 indicated the level of asymmetry apparent in step characteristics for two trained sprint runners. Whilst the magnitude of step characteristic asymmetry was low, it was significant for all variables for one athlete. Asymmetry was larger for either SL or SF than SV. To gain further understanding of the asymmetry apparent in sprint running and to gain insight into the causes of the significant asymmetry seen in step characteristics, further analysis of key kinematic variables is required.

The review of literature in Chapter 2 presented an apparent lack of research into the asymmetry of sprint running kinematics. Quantification of kinematic asymmetry is important from a data collection perspective to determine whether data must be collected bilaterally or whether symmetry can be assumed (Karamanidis et al., 2003). Running asymmetry has been investigated from an injury perspective, with asymmetry advocated as a possible contributor to injury predisposition in one side (Zifchock et al., 2006). From a performance perspective, there is no consensus in the results of studies that have investigated asymmetry in submaximal running. Vagenas and Hoshizaki (1992) reported significant asymmetry in kinematics of the lower extremity. Conversely, Karamanidis et al. (2003) concluded that unilateral data collection was sufficient for submaximal running due to the relatively low asymmetry of most kinematic variables, such as angular displacement and CT. However, other variables reported by Karamanidis et al. (2003) displayed a greater amount of asymmetry (angular velocity, flight time).

The Symmetry Index (SI) has been used in many studies of asymmetry in submaximal running (Karamanidis et al., 2003; Robinson et al., 1987; Vagenas & Hoshizaki, 1992; Zifchock et al., 2006). However, the SI is error prone due to the possible artificial inflation of variables that sit either side of zero (Herzog et al., 1989; Zifchock et al., 2008b). The \( \theta_{\text{SYM}} \) provides an alternative measure that overcomes the problem of artificially inflated values. A limitation of the \( \theta_{\text{SYM}} \) presented by Zifchock et al. (2008b) is the omission of intra-limb variability in the calculation of asymmetry, which could lead to large amounts of intra-limb...
variability resulting in falsely inflated asymmetry values. To the knowledge of the
author, none of the previous measures of asymmetry have sought to provide an
overall score of asymmetry for a participant and are instead used to assess
asymmetry of individual variables. An overall asymmetry measure would be useful
when classifying asymmetry levels of different athletes. Sprint running is known to
be highly variable on an inter-athlete basis with some sprinters being SL dominant
and others being SF dominant (Bezodis, 2006). Therefore, to allow asymmetry to
be compared on an inter-athlete level, a measure of asymmetry that combines
multiple variables associated with successful sprinting is required. An overall
measure of asymmetry may also be of use to coaches as it could highlight
potential injury predisposition in certain athletes (Zifchock et al., 2006).

A difficulty encountered when investigating asymmetry of multiple steps is natural
SV variability occurring from one step to the next, as demonstrated in Chapter 3.
SV directly influences success in sprint running; therefore, it may be beneficial to
consider changes in other kinematics relative to changes in SV. Asymmetry
analysis of sprint kinematics, without considering the natural changes in SV, could
lead to potential errors in asymmetry values that are actually due to slight changes
in SV. Therefore, it would be useful to include these changes in velocity when
developing a score of asymmetry to be used across different athletes.

The aim of this study was to investigate kinematic asymmetry of the lower limbs
during sprint running. To achieve this aim, four main questions will be addressed:

1. How can the level of kinematic asymmetry during sprint running be
   quantified for different athletes?
2. How asymmetrical are lower-limb kinematics of sprint running?
3. How consistent is the level of kinematic asymmetry across a range of
   athletes of varied ability?
4. Based on the level of asymmetry present, how appropriate is it to collect
   unilateral kinematic data on sprint running?

It was expected that the amount of asymmetry would vary on an inter-athlete level,
as is the case with other kinematic variables previously investigated within sprint
running (Bezodis, 2006; Johnson & Buckley, 2001). When comparing the
asymmetry of sprint running to that of submaximal running, it was expected that
there would be greater asymmetry apparent during sprint running due to the athlete performing maximally. When performing on the limit of ability any imbalances in strength or range of motion were expected to be emphasised.

4.2 Method

4.2.1 Participants
Ten participants volunteered for the study, all of whom were athletes that received sprint coaching as part of their athletic training. Ethical approval for the study was gained from the University Research Ethics Committee. Athletes gave written informed consent (Appendix A.6) to participate in the study and parental consent was obtained for athletes that were under 18 years of age. Athletes were all free from injury at the time of data collection. Data collections were carried out between November and December, when athletes were beginning to prepare for the indoor competitive season. Measurements of each athlete’s height and mass were taken on the day of data collection. Athlete profiles are presented in Table 4.1.

Table 4.1. Athlete profiles showing physical characteristics and personal best (PB) times.

<table>
<thead>
<tr>
<th>Athlete #</th>
<th>Height (m)</th>
<th>Mass (kg)</th>
<th>Age (years)</th>
<th>Event</th>
<th>PB (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>1.74</td>
<td>73.7</td>
<td>25</td>
<td>100 m</td>
<td>11.00*</td>
</tr>
<tr>
<td>02</td>
<td>1.81</td>
<td>78.3</td>
<td>21</td>
<td>100 m</td>
<td>10.67*</td>
</tr>
<tr>
<td>03</td>
<td>1.80</td>
<td>74.6</td>
<td>30</td>
<td>100 m</td>
<td>11.20*</td>
</tr>
<tr>
<td>04</td>
<td>1.79</td>
<td>67.9</td>
<td>24</td>
<td>400 m</td>
<td>50.65***</td>
</tr>
<tr>
<td>05</td>
<td>1.84</td>
<td>82.9</td>
<td>22</td>
<td>100 m</td>
<td>11.39*</td>
</tr>
<tr>
<td>06</td>
<td>1.86</td>
<td>85.2</td>
<td>21</td>
<td>100 m</td>
<td>10.86*</td>
</tr>
<tr>
<td>07</td>
<td>1.70</td>
<td>72.2</td>
<td>17</td>
<td>200 m</td>
<td>23.03**</td>
</tr>
<tr>
<td>08</td>
<td>1.78</td>
<td>62.9</td>
<td>19</td>
<td>200 m</td>
<td>23.70**</td>
</tr>
<tr>
<td>09</td>
<td>1.81</td>
<td>71.6</td>
<td>16</td>
<td>200 m</td>
<td>23.80**</td>
</tr>
<tr>
<td>10</td>
<td>1.65</td>
<td>57.7</td>
<td>15</td>
<td>200 m</td>
<td>23.80**</td>
</tr>
</tbody>
</table>

PB times relate to: * 100 m, ** 200 m and *** 400 m.

4.2.2 Data Collection
Data were collected at the National Indoor Athletics Centre, Cardiff. A four scanner CODA cx1 motion analysis system (Charnwood Dynamics, Leicester, UK) was
used, at a sampling rate of 200 Hz. Scanners were vertically mounted on customised tripods so that their mid points were raised to a height of 1.30 m above the track surface. Scanners were positioned 4.20 m from the centre of the running lane, at a separation of 4.00 m along the lane (Fig. 4.1). This setup maximised the length of the field of view in the sagittal plane (approximately 8.20 m), which ensured that a minimum of two full steps (up to a length of 2.73 m) were collected from every trial. The data capture area was centred 45.00 m from the start of each run. Cables connecting the two scanners on the far side of the track to the control computer were suspended 3.20 m above the track.

Figure 4.1. Location of CODA scanners showing field of view of each scanner (shaded area).

The CODA system was aligned according to the manufacturer’s guidelines. Alignment involved placing three markers on a horizontal plane (the track surface) to form two perpendicular vectors representing the x and y axes, intercepting at the origin. The x, y and z axes were defined as the medio-lateral, antero-posterior and vertical axes, respectively. The z axis was calculated as perpendicular to the plane mapped by the x and y axes. Twelve active CODA markers, connected in pairs to ‘twin-marker drive boxes’, were attached to each athlete using double-
sided adhesive tape prior to testing. Markers were located lateral to the fifth metatarsal-phalangeal (MTP) joint, lateral malleolus, lateral condyle of the tibia, greater trochanter, iliac crest and greater tubercle for both sides of the body (Fig. 4.2). Athletes performed warm-up runs with the markers attached to check that the markers and tape did not inhibit movement and that markers were secure.

![Diagram of anatomical markers and drive boxes](image)

Figure 4.2. Stick figure representation of athlete showing locations of drive boxes (a) and surface anatomical markers (b).

Athletes performed their own warm-up under the guidance of their coach. Marker positional data were collected whilst athletes performed 60 m sprint runs. Athletes were instructed to run maximally through the data collection area to a finish line located 6.70 m afterwards. The finish line was located beyond the data collection area to reduce any effects of athletes slowing down in anticipation of the finish. The CODA system was triggered manually following athletes’ first movements from their starting position. Six athletes (Athletes 1 to 6) performed twelve trials over two separate sessions. The remaining four athletes were available for one session and performed nine runs in that session; this was a familiar number of repetitions for these athletes to perform and formed part of their regular sprint training. Trials were rejected if an athlete noticeably altered their running style during the data collection area, or if any markers either became dislodged or were out of view for a period of eight or more epochs (0.040 s). Recovery time between trials was self-selected and typically lasted for approximately 10 minutes. Step
velocity was compared for trials completed in separate sessions by the same athlete to check that there were no significant (p<0.05) inter-session differences before data were pooled for each athlete (Appendix A.3).

4.2.3 Data Processing
Data acquired using the CODA system were processed using the kinematic_asym program (Appendix B) written in MATLAB (R2009b, The Mathworks, USA). Johnson and Buckley (2001) identified the dominance of sagittal plane movements in sprint running. Therefore, two-dimensional sagittal plane coordinates were extracted from the three-dimensional marker coordinates and used for further calculations. Sections of data where markers became occluded during a trial were replaced with data calculated via an interpolating cubic spline. Occluded data were identified using the internal logical ‘in-view’ variable generated by the CODA system during data collection. Occlusion occurred when athletes obscured markers, such as when a hand passed in front of hip and iliac markers; this typically lasted for six epochs (0.030 s). Horizontal and vertical coordinates for each marker were filtered via a fourth order low-pass Butterworth filter. Cut-off frequencies were calculated using Challis’ (1999) autocorrelation method via the autocor_CO program (Appendix B) and based on 0.1 Hz steps in cut-off frequency ranging from 1 to 95 Hz. Instants of TD were determined using peak vertical acceleration of the MTP markers (Bezodis et al., 2007; Hunter et al., 2004a).

4.2.4 Data Analysis
4.2.4.1 Calculation of Kinematic Variables
2D joint angles were calculated as vector angles between two adjacent segments in the sagittal plane (e.g. foot and shank segments were used for calculation of the ankle joint) using the cosine rule:

$$\theta = \arccos \frac{a^2 + b^2 - c^2}{2ab}$$  \[4.1\]

- $a =$ vector representing proximal segment
- $b =$ vector representing distal segment
- $c =$ vector joining the two markers not located on the joint centre for which the angle is being calculated.
Hip joint angles were calculated between thigh and pelvis segments with the pelvis defined between the hip and iliac markers. This definition was chosen to eliminate the influence of upper body movement on hip angle. Due to the cyclical motion of the upper limbs that has been indicated as maintaining balance during sprint running (Mann, 1981), inclusion of shoulder movement could affect the hip joint angle and related measures of asymmetry. Since the aim of this study was to quantify asymmetry of lower-limb kinematics, it was important that upper body movement did not influence the eight variables selected for analysis.

These variables were chosen based on three criteria: 1. biomechanical justification linked with successful sprint running performance; 2. variables that have been frequently reported in research studies into sprint running; 3. identification by expert sprint coaches as being central to successful sprinting (Thompson et al., 2009). Table 4.2 shows the variables that were used for this study along with their justification for inclusion. The variables analysed are shown graphically in Appendix A.2 for clarification.

**Table 4.2. Justification for the inclusion of selected kinematic variables in analysis.**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>SV</td>
<td>Criterion measure of success (Hay, 1994)</td>
</tr>
<tr>
<td>SL</td>
<td>Direct influence on SV (Hay, 1994; Hunter et al., 2004a)</td>
</tr>
<tr>
<td>SF</td>
<td>Direct influence on SV (Hay, 1994; Hunter et al., 2004a)</td>
</tr>
<tr>
<td>$z_{H_{MIN}}$</td>
<td>Coach interviews identified ‘high hips’ as a high-order construct (Thompson et al., 2009), the measure has also been used to determine vertical movement during stance (Hunter et al., 2004b)</td>
</tr>
<tr>
<td>$z_{K_{MAX}}$</td>
<td>Result of knee lift, identified by coaches as a desirable factor (Thompson et al., 2009)</td>
</tr>
<tr>
<td>$\theta_{MIN-FLEX}$</td>
<td>Biomechanical construct, greater knee flexion reduces the moment of inertia of the leg, allowing more rapid recovery (Hay, 1994)</td>
</tr>
<tr>
<td>$\theta_{H_{MAX-EXT}}$</td>
<td>Biomechanics literature (Hunter et al., 2004b; Mann, 1985)</td>
</tr>
<tr>
<td>$y_{TD}$</td>
<td>Biomechanics literature and coach interviews, due to a larger value increasing detrimental braking (Hunter et al., 2004a; Mann, 1985; Thompson et al., 2009)</td>
</tr>
</tbody>
</table>
SV and SL were calculated from the antero-posterior displacement of the mid-iliac and MTP marker locations from TD of one foot, to the subsequent TD of the contra-lateral foot. SF was calculated as the quotient of SV and SL. zH\text{MIN} and zK\text{MAX} were calculated as the minimum mid-hip height and maximum knee height of the contralateral limb during stance. θK\text{MIN-FLEX} and θH\text{MAX-EXT} were calculated as the knee angle during greatest flexion and hip angle during greatest extension during the stance phase. Values for y\text{TD} were calculated as the antero-posterior displacement between the MTP marker and mid-iliac at TD.

All kinematic results were normalised to allow comparisons of asymmetry between different variables and across athletes. Normalisation was achieved by dividing the mean value for the left and right sides by the overall maximum value of both sides for that athlete, then multiplying the result by 100%:

\[
X_{\text{NORM \_SIDE}} = \frac{X_{\text{MEAN \_SIDE}}}{\text{MAX}(X_{\text{BOTH}})} \times 100\% 
\]

\[4.2\]

\[ X_{\text{NORM \_SIDE}} = \text{normalised value for specific side} \]
\[ X_{\text{MEAN \_SIDE}} = \text{mean un-normalised value for specific side} \]
\[ \text{MAX}(X_{\text{BOTH}}) = \text{maximum un-normalised value of both sides} \]

Kinematic results were tested for normality using the criteria of Peat and Barton (2005). First, if the difference between the mean and median was ≤ 10%, the data were accepted as displaying a normal distribution. Any data that did not satisfy the first test then had to breach two out of four additional tests to be considered as having a non-normal distribution. These additional tests were: 1. the mean and standard deviation test, checking whether the magnitude of two standard deviations of the data was less than the mean value; 2. a Shapiro-Wilks test for normality; 3. skewness and kurtosis statistics being < 1; 4. the result of skewness or kurtosis divided by standard error being ≤ 1.96.

4.2.4.2 Development of a Global Measure of Asymmetry
For each of the calculated variables, absolute symmetry angle (ABSθ\text{SYM}) values were calculated using a modified version of the equation presented by Zifchock et al. (2008b):
ABSθ_{SYM} = absolute symmetry angle
X_{left} = value for the left side
X_{right} = value for the right side

ABSθ_{SYM} was calculated in favour of the standard θ_{SYM} as it allowed significant difference between the asymmetry apparent within different variables to be calculated. Without calculating absolute values, the calculation of significant difference in the amount of asymmetry would not have been possible due to the likely variation in polarity caused by differences in the direction of asymmetry.

In addition to the ABSθ_{SYM}, a measure of overall asymmetry was sought for each athlete. A new method was required that allowed comparison of overall asymmetry and also considered the significance of the difference between limbs relative to intra-limb variability. The overall score of kinematic asymmetry combined ABSθ_{SYM} scores for each variable and was termed the ‘kinematic asymmetry score’ (KMAS). The KMAS was initially calculated via four different methods. The results of each method were assessed against each athlete’s ABSθ_{SYM} values so that the score best representing athletes’ overall asymmetry could be selected.

The first method (KMAS₁) involved summing the ABSθ_{SYM} for each variable; this method was the simplest and did not take account of the asymmetry in SV:

\[ KMAS_1 = \sum_{i=1}^{n} ABSθ_{SYM}(x_n) \]  \hspace{1cm} [4.4]

\( KMAS_1 = \text{overall kinematic asymmetry score for athlete} \)
\( ABSθ_{SYM}(x_n) = \text{absolute symmetry angle for variable ‘}x_n\text{’} \)

For the other three methods of calculating KMAS (KMAS₂₋₄) statistical significance was utilised to provide a weighting for each variable based on its asymmetry. Following the test for normality described in the previous section, all data were
accepted as being normally distributed; therefore, parametric statistics were used to test for significant differences. All statistical tests were run on an intra-athlete basis due to the individual nature of sprint running and the potential problems associated with group analyses outlined by Dufek et al. (1995). Statistical tests were performed using SPSS version 17.0 (Chicago, USA). A t-test was utilised to determine the significance of differences in normalised results from left and right sides of the body; this was termed ‘absolute difference factor’ (ADF). The t-test results were interpreted at the 95% confidence level (Vincent, 2005). In addition to the ADF, a repeated-measures ANOVA was employed to determine the significance of differences in the $\text{ABS}0_\text{SYM}$ calculated for SV and each other variable; this measure was termed ‘relative difference factor’ (RDF).

KM$\text{AS}_{2-4}$ values were then calculated using Equations 4.5 and 4.6, although with slight variations in how the RDF was calculated. For KM$\text{AS}_2$, RDF was determined using the mean value of $\text{ABS}0_\text{SYM}$ for SV across all trials; kinematic variables were considered to have ‘relative difference’ if their mean $\text{ABS}0_\text{SYM}$ was greater than the mean +1SD value for SV. KM$\text{AS}_3$ used RDF values based on the ANOVA results with a significance level of $<0.05$. Finally, KM$\text{AS}_4$ was calculated similarly to KM$\text{AS}_3$, but with the Bonferroni correction applied (Vincent, 2005) to maintain a 95% confidence level. Applying the Bonferroni correction for an ANOVA including eight variables resulted in the significance level for the ANOVA being reduced to $<0.006$ (0.05 divided by 8).

To calculate KM$\text{AS}_{2-4}$, first a score of asymmetry was calculated for each variable based on the product of the $\text{ABS}0_\text{SYM}$ and the results of the ADF and RDF:

$$\text{KMAS}(x_n) = (\text{ADF} + \text{RDF}) \times \text{ABS}0_\text{SYM}(x_n)$$  \hspace{1cm} [4.5]

$\text{KMAS}(x_n) =$ kinematic asymmetry score for variable ‘$x_n$’

ADF = either 0 or 1 depending on the result of the ADF test of significant difference, with 1 indicating a significant difference between values for the left and right side

RDF = either 0 or 1 depending on the result of the RDF test of significant difference, with 1 indicating a significant difference between the $\text{ABS}0_\text{SYM}$ for the specific variable and that of SV
ABSθSYM(x_n) = absolute symmetry angle for variable ‘x_n.’

For KMAS_{2,4}, the overall asymmetry score for each athlete was then calculated as the sum of the scores for all variables:

\[ KMAS = \sum_{i=1}^{n} KMAS(x_n) \]  \[4.6\]

\( KMAS = \) overall kinematic asymmetry score for athlete
\( KMAS(x_n) = \) kinematic asymmetry score for variable ‘x_n.’

4.3 Results

4.3.1 Mean Kinematic Variables
Table 4.3 contains mean kinematic results for each athlete. Results are grouped according to the step during which the measurement was taken; step L-R includes SV, SL and SF from the left to right step and \( z_{H_{\text{MIN}}}, zK_{\text{MAX}}, \theta K_{\text{MIN-FLEX}}, \theta H_{\text{MAX-EXT}} \) and \( y_{TD} \) for the left leg; step R-L refers to variables for the contralateral side. L-R and R-L step differences varied between athletes as did the amount of intra-limb variability, demonstrated by the range of SD values for each variable. Results in Table 4.3 were also normalised relative to each athlete’s maximum values, normalised values can be found in Appendix A.4 (Table A.3).

4.3.2 Asymmetry Results
Figures 4.3 to 4.12 illustrate ABSθSYM results and normalised mean kinematic results for both L-R and R-L steps. The top half of each figure displays the mean ABSθSYM for each kinematic variable. The highlighted area of the top section indicates the mean +1SD for SV, with the mean value shown by the dashed line. This allows visual comparison of SV asymmetry with that of the other variables and shows the relative significance threshold used for the calculation of KMAS_{2}. The bottom section of each figure shows normalised mean results of each step for all variables. Also indicated on the figures are the results of the ADF and RDF tests for each athlete used in the calculation of KMAS_{4}. An asterisk indicates that there was a significant difference (\( p<0.05 \)) between sides and a highlighted box indicates that a variable has a significantly larger (\( p<0.006 \)) ABSθSYM than SV.
Table 4.3. Mean [± SD] kinematic results for L-R and R-L steps for each athlete.

<table>
<thead>
<tr>
<th>Athlete</th>
<th>SV (m∙s⁻¹)</th>
<th>SL (m)</th>
<th>SF (Hz)</th>
<th>zH_MIN (m)</th>
<th>zK_MAX (m)</th>
<th>θK_MIN-FLEX (°)</th>
<th>θH_MAX-EXT (°)</th>
<th>y_TD (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L-R</td>
<td>R-L</td>
<td>L-R</td>
<td>R-L</td>
<td>L-R</td>
<td>R-L</td>
<td>L-R</td>
<td>R-L</td>
</tr>
<tr>
<td>01</td>
<td>8.75</td>
<td>8.54</td>
<td>2.14</td>
<td>2.08</td>
<td>4.09</td>
<td>4.12</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>02</td>
<td>8.95</td>
<td>8.79</td>
<td>2.22</td>
<td>2.30</td>
<td>4.03</td>
<td>3.82</td>
<td>0.92</td>
<td>0.91</td>
</tr>
<tr>
<td>03</td>
<td>9.05</td>
<td>8.95</td>
<td>2.27</td>
<td>2.28</td>
<td>3.99</td>
<td>3.92</td>
<td>0.89</td>
<td>0.88</td>
</tr>
<tr>
<td>04</td>
<td>8.58</td>
<td>8.54</td>
<td>2.10</td>
<td>2.19</td>
<td>4.08</td>
<td>3.91</td>
<td>0.91</td>
<td>0.90</td>
</tr>
<tr>
<td>05</td>
<td>9.31</td>
<td>9.29</td>
<td>2.38</td>
<td>2.34</td>
<td>3.91</td>
<td>3.97</td>
<td>0.89</td>
<td>0.90</td>
</tr>
<tr>
<td>06</td>
<td>10.20</td>
<td>10.09</td>
<td>2.55</td>
<td>2.53</td>
<td>4.53</td>
<td>4.34</td>
<td>0.92</td>
<td>0.94</td>
</tr>
<tr>
<td>07</td>
<td>9.08</td>
<td>8.99</td>
<td>1.95</td>
<td>1.95</td>
<td>4.67</td>
<td>4.61</td>
<td>0.90</td>
<td>0.89</td>
</tr>
<tr>
<td>08</td>
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<td>8.91</td>
<td>2.26</td>
<td>2.25</td>
<td>3.93</td>
<td>3.96</td>
<td>0.86</td>
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</tr>
<tr>
<td>09</td>
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<td>8.72</td>
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<td>4.09</td>
<td>4.13</td>
<td>0.89</td>
<td>0.90</td>
</tr>
<tr>
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<td>9.17</td>
<td>1.93</td>
<td>1.95</td>
<td>4.78</td>
<td>4.70</td>
<td>0.85</td>
<td>0.84</td>
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</tbody>
</table>
Figure 4.3. Mean $\text{ABS} \theta_{\text{SYM}} [+1\text{SD}]$ (top) and mean normalised kinematic measures (bottom) for Athlete 1. Step L-R shown in black, R-L in grey.

Figure 4.4. Mean $\text{ABS} \theta_{\text{SYM}} [+1\text{SD}]$ (top) and mean normalised kinematic measures (bottom) for Athlete 2. Step L-R shown in black, R-L in grey.
Figure 4.5. Mean $\text{ABS}\theta_{\text{SYM}} [+1\text{SD}]$ (top) and mean normalised kinematic measures (bottom) for Athlete 3. Step L-R shown in black, R-L in grey.

Figure 4.6. Mean $\text{ABS}\theta_{\text{SYM}} [+1\text{SD}]$ (top) and mean normalised kinematic measures (bottom) for Athlete 4. Step L-R shown in black, R-L in grey.
Figure 4.7. Mean $\text{ABS}\theta_{\text{SYM}}$ [+1SD] (top) and mean normalised kinematic measures (bottom) for Athlete 5. Step L-R shown in black, R-L in grey.

Figure 4.8. Mean $\text{ABS}\theta_{\text{SYM}}$ [+1SD] (top) and mean normalised kinematic measures (bottom) for Athlete 6. Step L-R shown in black, R-L in grey.
Figure 4.9. Mean $\text{ABS}_{\text{SYM}} [+1\text{SD}]$ (top) and mean normalised kinematic measures (bottom) for Athlete 7. Step L-R shown in black, R-L in grey.

Figure 4.10. Mean $\text{ABS}_{\text{SYM}} [+1\text{SD}]$ (top) and mean normalised kinematic measures (bottom) for Athlete 8. Step L-R shown in black, R-L in grey.
Figure 4.11. Mean $\text{ABS}\theta_{\text{SYM}} [+1SD]$ (top) and mean normalised kinematic measures (bottom) for Athlete 9. Step L-R shown in black, R-L in grey.

Figure 4.12. Mean $\text{ABS}\theta_{\text{SYM}} [+1SD]$ (top) and mean normalised kinematic measures (bottom) for Athlete 10. Step L-R shown in black, R-L in grey.
All athletes displayed a range of $\text{ABS} \theta_{\text{SYM}}$ for different variables. SV tended to show the least asymmetry, which is illustrated by the location of the dashed line relative to the other variables. SL and SF were more asymmetrical than SV for all athletes but neither variable displayed the most asymmetry of all variables measured for any athlete. Athletes 4 and 7 appeared to display the most asymmetry with two variables having $\text{ABS} \theta_{\text{SYM}}$ values greater than 4%. Combining the top and bottom sections of Figures 4.3 to 4.12 is advantageous as it gives an indication of the consistency of each variable’s asymmetry and whether it is side dependent for each athlete. An example of this is Athlete 1’s $\text{ABS} \theta_{\text{SYM}}$ results, where the value for $y_{\text{TD}}$ was the second largest of all variables (2.6%). However, the direction of the asymmetry was not consistent across trials, illustrated by the similarity of the mean left and right values as shown in the bottom section of Figure 4.3. Conversely, Athlete 6’s $\text{ABS} \theta_{\text{SYM}}$ result for SF was the fourth largest for this athlete; however, the bottom section of Figure 4.8 shows that the difference between left and right mean values was greatest for this variable, indicating consistency in the direction of the asymmetry. The most frequent variable to display a significant difference in the mean values between left and right was SV, with six athletes. The next most common variables to display a significant difference between the left and right side were $z_{\text{KMAX}}$ and $\theta_{\text{KMIN-FLEX}}$, both showing a significant difference for five athletes. Four athletes displayed significant differences in SL and $\theta_{\text{HMAX-EXT}}$. The remaining variables (SF, $z_{\text{HMIN}}$ and $y_{\text{TD}}$) showed a significant difference between mean left and right values for three or fewer athletes.

The asymmetry profiles presented in Figures 4.3 to 4.12 give a graphical representation of the amount of kinematic asymmetry present for each athlete. Athlete 4 displayed the greatest amount of asymmetry whilst Athlete 9 appeared to be the least asymmetrical. However, it is difficult to compare the asymmetry of the remaining athletes using just the asymmetry profiles. The KMAS values calculated for each athlete allowed comparison of overall asymmetry between athletes. Figure 4.13 displays the results of the four different methods used to calculate KMAS for each athlete. There were notable differences in the resulting KMAS calculated using the different methods. The greatest difference was between KMAS$_1$ and the other three methods for Athlete 4, where the difference was larger than 10. The values calculated using KMAS$_1$ showed less range (7.86) than the
other three methods (24.74, 22.29 and 23.08). Athletes 4 and 9 displayed the greatest and least amount of asymmetry, respectively for all methods.

![Figure 4.13. KMAS values calculated using four different methods for each athlete.](image)

**4.4 Discussion**

The aim of this study was to investigate the level of kinematic asymmetry present in the lower limbs during sprint running. This section discusses the development of novel scores of kinematic asymmetry, inter-athlete asymmetry differences and the implications of the observed asymmetry on unilateral methods of data collection.

**4.4.1 Quantifying Global Kinematic Asymmetry**

Comparing the results of the different methods used to calculate KMAS (Fig. 4.13), there was a large difference between the results of KMAS1 and the other three methods. KMAS1 was the only method that did not consider statistical significance relative to SV. Due to six out of the ten athletes displaying a significant difference between SV results for L-R and R-L steps, it was decided that asymmetry of SV should be incorporated in the global KMAS. Therefore, KMAS1 was deemed an unsuitable score of global asymmetry. The results of the three remaining methods displayed greater agreement between methods. KMAS2 related asymmetry values to those for SV but did not have statistical significance. Comparing the statistical results for calculating relative difference (RDF) with the use of the ‘cut-off threshold’ identified on Figures 4.3 to 4.12, it was evident that the use of the visual
method could lead to more variables being included in the KMAS. An example of this was apparent for Athlete 10, where all seven kinematic variables are above the threshold defined by the SV asymmetry. However, only three of these ($z_{K_{\text{MAX}}}$, $\theta_{H_{\text{MAX-EXT}}}$ and $y_{TD}$) variables displayed a statistically significant difference with SV. Due to the possibility of artificially inflated asymmetry results when using KMAS$_2$, this method was also eliminated. KMAS$_3$ and KMAS$_4$ displayed very similar results, with KMAS$_3$ producing slightly higher results for all athletes. The importance of correcting confidence levels when performing statistical tests with repeated measures has been widely publicised (Bland & Altman, 1995; Field, 2009; Vincent, 2005), so as to reduce the occurrence of Type I Errors. The effects of not performing this correction are highlighted by the fact that KMAS$_3$ produced consistently larger values than KMAS$_4$ for each athlete. For this reason, KMAS$_3$ was also rejected and KMAS$_4$ was selected as the most appropriate score of an athlete’s overall asymmetry. The remainder of this discussion will focus on KMAS$_4$ as the global measure of athletes’ kinematic asymmetry. The development of a global measure of kinematic asymmetry allowed comparison of overall kinematic asymmetry between athletes and also facilitated the inter-athlete comparison of kinematic asymmetry with other factors, such as kinetic asymmetry.

The variable that was most frequently included in the calculation of KMAS$_4$ across all athletes was $\theta_{K_{\text{MIN-FLEX}}}$, this was included based on results of both the ADF and RDF for five of the athletes and solely for the RDF results for a further two athletes. A possible explanation for the frequent inclusion of $\theta_{K_{\text{MIN-FLEX}}}$ is the inter-limb differences in range of motion that may be emphasised when performing maximally. The next most frequently included variable was $y_{TD}$ which was included based on both tests for two athletes and just for RDF for a further six athletes.

The variable that had the least influence on the calculation of KMAS$_4$ was $z_{H_{\text{MIN}}}$, which was included because of the ADF results for just two athletes and was not included for any athlete when using the RDF results. The low influence of $z_{H_{\text{MIN}}}$ is in agreement with the results of Karamanidis et al. (2003) for submaximal running, who reported values for minimum hip height that relate to an ABS$\theta_{\text{SYM}}$ of 0.41%. These authors also found that when measuring hip height at different points during stance (TD, minimum height and TO), it consistently had the smallest asymmetry value out of the variables analysed. This finding supports the use of the selected
measures of asymmetry. When comparing the results presented in Table 4.3, \( z_{\text{H}_\text{MIN}} \) displayed the least asymmetry of all variables, this may be necessary to prevent collapse of the limb during the support phase.

\( \text{ABS} \theta_{\text{SYM}} \) for SF was significantly larger than SV for four athletes, whilst the remaining variables (\( \text{SL, z}_{\text{K}_{\text{MAX}}}, \theta_{\text{H}_{\text{MAX,EXT}}} \) and \( z_{\text{H}_\text{MIN}} \)) showed significant difference in asymmetry with SV for three or fewer athletes. \( z_{\text{H}_\text{MIN}} \) was the only variable that did not show a significant difference in \( \text{ABS} \theta_{\text{SYM}} \) with SV for any athletes.

Due to KMAS\(_4\) incorporating a number of measures of kinematic asymmetry, it was possible for athletes to have a similarly large KMAS\(_4\) score due to either one largely asymmetrical variable or numerous moderately asymmetrical variables. This was an inherent feature of KMAS\(_4\) and justifies its use; if this were not the case, an athlete could display a very large asymmetry in one specific variable that does not affect other variables and the magnitude of the asymmetry would be masked by the symmetry of other variables. When comparing Figures 4.3 to 4.12 it appears that large KMAS\(_4\) scores, such as those shown by Athletes 4, 7 and 8, were produced both by the athlete having numerous variables identified as significant by the RDF and therefore included in the KMAS\(_4\) calculation and also from having one or two particularly large \( \text{ABS} \theta_{\text{SYM}} \) scores. Athletes with low KMAS\(_4\) values, such as Athletes 3, 9 and 10, displayed \( \text{ABS} \theta_{\text{SYM}} \) results for the kinematic variables close to that calculated for SV, with the largest \( \text{ABS} \theta_{\text{SYM}} \) for any variable being less than 4%.

4.4.2 Asymmetry of Lower-Limb Kinematics

\( \text{ABS} \theta_{\text{SYM}} \) values for SV was either the lowest or second lowest out of all variables for every athlete. However, in some cases mean L-R and R-L values were more similar for other variables than for SV. This was evident for Athlete 1, where the difference in mean SV was 2.38% compared to 0.02% for \( y_{\text{T}_\text{D}} \) (Appendix A.3). Similar mean values for left and right sides with a large \( \text{ABS} \theta_{\text{SYM}} \) for the variable indicates that for \( y_{\text{T}_\text{D}} \) for Athlete 1, asymmetry was high within each trial but that the direction of the asymmetry was inconsistent, resulting in similar mean values for the left and right sides. These occurrences did not affect the calculation of KMAS\(_4\) due to the inclusion of statistical tests. Figure 4.3 indicates that \( y_{\text{T}_\text{D}} \) was not
significant in either test for Athlete 1, so the inconsistent asymmetry is not included in the KMAS₄ for that athlete.

Similarities can be drawn between the results of this study and those in Study 2 of Chapter 3. For the two athletes tested in the previous study, the magnitude of SV asymmetry was less than SF; furthermore, the direction of the SL and SF asymmetry was opposite in direction causing the smaller SV asymmetry. This finding is reiterated in the results of all ten athletes tested in this study, with the magnitude of SV asymmetry values being in between those of SL and SF. The direction of asymmetry for SL and SF was opposite for all athletes tested; i.e. if SL was greater for the L-R step, SF was always greater for the R-L step and vice-versa. It appears that the asymmetry of SL and SF may tend to be opposite in direction due to the negative interaction between the two variables reported in previous studies into step characteristics (Donati, 1995; Hunter et al., 2004a).

Comparing the asymmetry results to those reported by Karamanidis et al. (2003) for submaximal running, there was greater asymmetry present in this study. One possible explanation for this difference could be the difference in velocity between the two studies. Karamanidis et al. (2003) collected data from runners at velocities of 3.50 m·s⁻¹ or less, compared to a mean SV of 9.03 m·s⁻¹ in this study. This comparison suggests that asymmetry may be larger when sprinting than when running at slower velocities. One possible reason for increased asymmetry when performing maximally could be that the athlete is pushing each side to its limit and emphasising any imbalances in strength and ranges of motion, evident in the large occurrence of significant asymmetry in θK_MIN-FLEX.

4.4.3 Consistency of Kinematic Asymmetry
KMAS₄ results showed that there was some asymmetry present for all athletes, but that the level of asymmetry varied greatly. The lowest asymmetry score was 4.52 for Athlete 9. This is reinforced by the fact that all ABSθSYM values were close to that of SV and that there were no significant differences between sides for any variables (Fig. 4.11). Conversely, the highest asymmetry score was 27.60 for Athlete 4, the asymmetry profile for this athlete (Fig. 4.6) stands out from the others as there are four variables identified by the RDF and five identified by the ADF as displaying significant asymmetry. Comparison of the bottom halves of
Figures 4.6 and 4.11 also highlights that there was far greater asymmetry shown by Athlete 4 than Athlete 9.

Figures 4.3 to 4.12, indicate that the amount of asymmetry present in most variables was not consistent across different athletes. This finding suggests that asymmetry should be considered on an individual athlete basis. To the knowledge of this author, there are no previous studies into asymmetry of sprint running to compare these findings with. However, the concept of individually specific analyses concurs with previous studies that have focussed on other aspects of sprint running and reported that results should be considered on an individual athlete basis (Bezodis, 2006; Johnson & Buckley, 2001). Inter-athlete differences in asymmetry indicated that asymmetry could be caused by individual strength or range of motion asymmetry.

4.4.4 Implications for Kinematic Data Collection
A range of asymmetry levels were seen for different variables and different athletes. Therefore, for variables and athletes displaying asymmetry, unilateral analyses could lead to significant differences apparent in the unanalysed limb being overlooked. In certain restricted environments, such as when collecting data in competition or aligning CODA scanners unilaterally (Gittoes & Wilson, 2010), it may only be possible to collect kinematic data from one side of the body. When this is the case, effort should be made to consider the asymmetry of the athlete and variables being studied and potential implications of this. Wherever possible, it is advised to conduct a pre-test analysis of asymmetry for each athlete to determine a suitable methodology (Ciacci et al., 2010). When this is not possible and kinematic data are to be collected from one side of the body, care should be taken when choosing which variables to measure and the possibility of asymmetry should be considered in such findings.

Considering the ramifications of this asymmetry analysis on the future collection of kinematic data; if a unilateral analysis of sprinting kinematics were to be performed for Athlete 9, very little information would have been lost about the motion of the contralateral side due to the high symmetry displayed by the athlete. However, if the same approach had been used for an analysis of Athlete 4, the results for one side would differ significantly from those of the other and could potentially lead to
misleading conclusions being drawn. An example of this potential error can be seen in the differences between mean $\theta_k^{\text{MIN-FLEX}}$ values for the left and right limbs of Athletes 4 (4.94°) and 9 (0.16°). In light of this finding and the suggestion by Vagenas and Hoshizaki (1991) that asymmetry may vary on an individual joint basis, a bilateral approach to kinematic data collection is recommended. It is understood that environmental limitations may not always permit consecutive steps to be collected; in such cases it is recommended that bilateral steps are collected from separate trials (Zifchock & Davis, 2008).

4.4.5 General Observations

Comparing the group mean values in Table 4.3 with those reported in previous studies (Mann & Herman, 1985; Mero & Komi, 1985) there are similarities in the results for SV, SL, SF, $\theta_k^{\text{MIN-FLEX}}$ and $y_{TD}$. These similarities indicate that the athletes recruited for this study are of a similar standard to those in previous studies of sprint running. Mean SV values ranged from 8.54 to 10.20 m·s$^{-1}$ across all athletes. A large range of values was also apparent for most other variables, with the exception of $zH_{\text{MIN}}$ which was similar for all athletes. The similarity in $zH_{\text{MIN}}$ values was unexpected, due to the range in athlete heights shown in Table 4.1.

There did not appear to be a relationship between performance and the level of asymmetry present for the athletes. Athletes 3 and 7 had similar mean velocities across all trials (9.00 and 9.04 m·s$^{-1}$, respectively). However, Athlete 3’s KMAS$_4$ (7.22) was less than half the magnitude of that calculated for Athlete 7 (15.43). Therefore, it does not appear that an athlete’s asymmetry can be estimated based on their sprinting ability.

Possible causes of asymmetry that have been suggested in previous research are strength imbalances and ‘lateral preference’ (Vagenas & Hoshizaki, 1991), referring to the favouring of one side. The authors specified that the idea of ‘limb dominance’ should be viewed with caution, suggesting that functional bilateralism should be looked at on an individual joint basis, rather than for each limb as a whole. Other reported possible causes of lower-limb asymmetry in submaximal running and walking gait are injury compensation and limb length discrepancy (Perttunen et al., 2004; Williams et al., 1987). This suggests that kinematic asymmetry may be the result of physiological or kinetic asymmetry of the athlete.
As suggested by Vagenas and Hoshizaki (1991), one possible explanation for kinematic asymmetry is a strength imbalance in the athlete. This could cause relatively large asymmetry in the observed kinematic variables, the effects of which could be reduced when analysing SV by the requirement for the athlete to run within a lane. A strength imbalance could also necessitate compensatory asymmetry to reduce the effect on kinematic variables and step characteristics (Beyaert et al., 2008). To gain understanding of potential compensatory kinetic mechanisms, an analysis of kinetic asymmetry could be performed. Studying the individual joint kinetics can provide greater understanding of the causes of movement (Winter, 1980), enhance understanding of the individual joint asymmetry (Vagenas & Hoshizaki, 1991) and may provide greater indication as to whether the kinematic asymmetry seen for some athletes could predispose one side of the athlete to injury more than the other (Zifchock et al., 2008a).

4.5 Conclusion

The results of this study have shown that kinematic asymmetry was present for all the athletes tested, but that the magnitude of asymmetry for each variable was not consistent between athletes. Four fundamental research questions were presented in Section 4.1 to guide the investigation of kinematic asymmetry. The responses to these research questions are presented here:

1. How can the level of kinematic asymmetry be quantified for different athletes?
A kinematic asymmetry score (KMAS₄) has been developed and rationalised for quantifying overall asymmetry of different athletes. This score incorporates numerous kinematic variables associated with successful sprint running.

2. How asymmetrical are lower-limb kinematics of sprint running?
Asymmetry was apparent for all ten athletes. θK_MIN-FLEX displayed the largest asymmetry whilst zH_MIN was the least asymmetrical. Asymmetry was smaller for step characteristics than other kinematic variables.
3. How consistent is the level of kinematic asymmetry across a range of athletes of varied ability?

The amount of asymmetry was not consistent, even across athletes of similar ability. There was a range in the $\text{ABS}_\text{SYM}$ scores seen for individual kinematic variables, as well as for overall $\text{KMAS}_4$.

4. Based on the level of asymmetry present, how appropriate is it to collect unilateral kinematic data on sprint running?

All of the variables analysed displayed significant differences between sides for some athletes. Based on the results of this study, it is recommended that unilateral analysis of sprint running should only be carried out with a careful consideration of the asymmetry of the specific athlete being studied.

To fully understand the causes of these asymmetries, further analysis is required of the kinetic variables that are responsible for causing the observed kinematics. Vagenas and Hoshizaki (1991) suggested that asymmetry may vary on an individual joint basis. Therefore, Chapter 5 will address asymmetry of the kinetics that are responsible for the movements analysed in this study, including a specific analysis of the kinetic asymmetry of the ankle, knee and hip joints.
CHAPTER 5 – KINETIC ASYMMETRY OF THE STANCE PHASE IN MAXIMAL VELOCITY SPRINT RUNNING

5.1 Introduction

Chapter 4 indicated that the magnitude of kinematic asymmetry varies on an inter-athlete level. It was also noted that the variables influencing an athlete’s KMAS were not consistent across different athletes. To gain understanding of the causes of the observed kinematic asymmetry variability seen in Chapter 4, an athlete-specific kinetic analysis was required (Hay, 1994).

Sprint running differs to other forms of running as athletes are performing at their body’s physical limits to achieve maximum velocity (Bushnell & Hunter, 2007). Working at high intensity often leads to sprint runners becoming injured (Schache et al., 2009; Yeung et al., 2009). It has been shown that repeated impact loading can lead to cartilage degeneration (Radin et al., 1973). Furthermore, the magnitudes of vertical impact forces experienced during sprint running are in excess of 3 BW (Belli et al., 2002; Schache et al., 2009). Therefore, a kinetic analysis could give greater insight into the potential increased predisposition to injury caused by asymmetries present in sprint running (Schache et al., 2009).

The logistics of kinetic data collection in maximal velocity sprint running offer different challenges to those encountered when collecting kinematic data. One such challenge relates to the collection of GRF data using a force plate. Force plates tend to measure up to ~1.00 m in length, which is a small section of a sprint run and less than half of a typical step length. The limited area of data collection, combined with the need to have the whole foot placed within the boundaries of the force plate invariably results in many trials being performed to allow successful contact of the athlete’s foot with the force plate without the athlete changing their step pattern to target the force plate. The need to perform a greater number of trials, along with the fact that it is often only possible to collect data from one foot contact per trial, means that very often data have been considered on a unilateral basis (Belli et al., 2002; Bezodis et al., 2008; Johnson & Buckley, 2001; Luhtanen & Komi, 1978), or information about which side of the body data were collected was not reported (Mann, 1981; Mann & Sprague, 1980). Based on the results of
Chapter 4, it was recommended that kinematic data should be collected bilaterally when possible and that when a unilateral approach is adopted, the effects of asymmetry should be considered in the analyses. Therefore, part of this chapter addresses kinetic data collection issues and the affects of kinetic asymmetry.

As with Chapters 3 and 4, the kinetic analysis was performed on an individual athlete basis due to large inter-athlete differences in sprint running kinetics. An IDA was employed to investigate kinetic asymmetry. Use of IDA allowed calculation of net moments around the ankle, knee and hip joints, as has been used previously to enhance understanding of the mechanical demands of sprint running (Bezodis et al., 2008; Hunter et al., 2004c; Johnson & Buckley, 2001). Vagenas & Hoshizaki (1991) suggested that asymmetry may vary on an individual joint basis and recommended analysing asymmetry for each joint separately, as opposed to generalising about each limb. Sadeghi et al. (2000) recommended power as a good indicator of kinetic asymmetry due to its inclusion of both the cause (joint moment) and effect (angular velocity) of a movement.

Therefore, the aim of this study was to investigate the kinetic asymmetry of the lower limbs during sprint running, in light of the kinematic asymmetry reported in Chapter 4. In order to accomplish this aim, four questions were addressed:

1. How can the level of kinetic asymmetry during sprint running be quantified for different athletes, considering multiple kinetic factors influential to sprint running?
2. How asymmetrical are lower-limb kinetics of sprint running?
3. How is kinetic asymmetry related to kinematic asymmetry during sprint running?
4. Based on the level of kinetic asymmetry present, is it appropriate and sufficient to collect unilateral kinetic data on sprint running?

It was hypothesised that kinetic asymmetry would vary between athletes, as with other kinetic analyses of sprint running (Bezodis et al., 2008; Johnson & Buckley, 2001). However, the author is unaware of previous work on kinetic asymmetry in sprint running that has investigated causes of kinematic asymmetry. Therefore, it was necessary to analyse the kinetic asymmetry to enhance understanding of the interaction between kinetic and kinematic asymmetry during sprint running.
5.2 Verification Study of Multiple Force Plate Collections

The use of force plates to collect kinetic data during sprint running has been common for many years (Mann, 1981; Mann & Sprague, 1980). Force plates have a reported resolution of 10 mN (Kistler Instruments Ltd., UK), an accuracy of ~1% (Kerwin, 1997) and can be mounted in various locations including laboratory floors and athletic tracks. For acceptable kinetic data to be collected, contact with the force plate must occur within the boundaries of the plate, so that the measured force is not affected by force being applied to the surrounding surface. The need for contact within the plate boundaries can lead to rejected trials if foot contacts overlap the boundaries of the plate (Johnson & Buckley, 2001), which increases the number of trials required to allow collection of sufficient data for analysis.

One problem associated with the use of force plates to collect sprint data is the size of the data collection area relative to an athlete’s step length. A typical force plate measuring 0.90 x 0.60 m covers less than half of a 2 m step. Abendroth-Smith (1996) noted the detrimental effects on data when athletes target the force plates to increase frequency of acceptable contacts, a notion that was reinforced by Challis (2001). Furthermore, as the full foot must contact the force plate within the boundary of the plate, an athlete wearing 0.30 m running spikes only has a 0.60 m window for successful contact with the plate (illustrated in Fig. 5.1).

![Figure 5.1. Force plate diagram showing area of rejected trials (shaded) and total length of acceptable foot contact area (0.60 m).](image-url)
A possible solution to increase the frequency of useable foot contacts from sprint trials is to utilise numerous force plates mounted end to end. The addition of a second force plate of equal size would double the track area of data collection and could also allow the possibility of collecting steps that overlap between plates. In the previously discussed example of an athlete wearing 0.30 m running spikes, the addition of a second plate could effectively increase the data collection area by 2.5 times if contacts across both plates are acceptable (Fig. 5.2).

![Diagram of two force plates mounted end-to-end showing area of rejected trials (shaded) and total length of acceptable foot contact area (1.50 m).](image)

Figure 5.2. Force plate diagram of two plates mounted end-to-end, showing area of rejected trials (shaded) and total length of acceptable foot contact area (1.50 m).

Contacts occurring across both plates result in all of the force being applied to the plates and not the surrounding track surface. However, errors could occur with the calculation of centre of pressure (COP), which is a required input when performing an inverse dynamic analysis. As COP is calculated relative to each force plate a method was required to treat the data so that a global COP location could be calculated from the data recorded by each force plate. Foot contacts that occur across two plates will inherently include a greater amount of error in COP.
calculation than contacts occurring in the middle of the plate, due to the contact occurring towards the extremities of both plates. Bobbert and Schamhardt (1990) reported that the accuracy of COP calculation for piezoelectric force plates was greatest at the centre of the plate, with the largest errors being present in the area outside of the plate’s sensors.

Therefore, the aim of this verification study was to determine whether COP could be determined sufficiently accurately for contacts occurring across two force plate to be used in subsequent IDA. The following additional research questions were addressed to meet this aim:

5. How accurate is COP calculation for data collected using two force plates?
6. What effect does error in COP calculation have on power values calculated using IDA?

5.2.1 Verification Study Data Collection
Data collection involved the use of a known mass being rolled over both plates on a fixed axle rigid trolley; this allowed a smooth transition from one plate to the other, in an antero-posterior motion similar to that of an athlete’s COP during a sprint trial. Data were collected at the National Indoor Athletics Centre in Cardiff. Two force plates (Kistler, 9287BA), each measuring 0.90 m x 0.60 m, were mounted in customised housings sunk into the floor under the track surface. Once positioned, the plates were separated longitudinally by a distance of 0.006 m; this stopped contact with one plate causing interference with the readings of the other plate. The plates were covered with Mondo track surface (Mondo, USA), which also covered the athletic track. Once the covering was in place, it was flush with the surrounding track surface. Both force plates were attached to individual force plate control units (Kistler, 5233a), which were connected to the CODA hub for triggering. Two CODA scanners (cx1) were positioned either side of the force plates, at a separation of 8.40 m (Fig. 5.3).
Figure 5.3. Location of CODA scanners relative to force plates. The CODA field of view (4.10 m along the lane) is shown by the shaded area.

The two CODA scanners were aligned according to the manufacturer’s recommendations, with the x, y and z axes defined as the medio-lateral, antero-posterior and vertical axes, respectively. The three axes of the CODA system were positioned so that they were parallel to the corresponding axes of the force plates. The CODA software collected kinetic data from the force plates at 1000 Hz. Marker positional data were collected at 800 Hz, which was the maximum sampling rate of the CODA system for positional data collection. Using the highest possible sampling frequency (800 Hz) for kinematic data collection restricts the number of markers that can be tracked to six, making it unsuitable for analysis of more complex movements requiring more than six markers. Three active CODA markers were attached to the top of a four-wheeled trolley. The trolley was loaded with a mass of 500 kg positioned above one wheel (Fig. 5.4). The force applied to the track surface by the loaded wheel was approximately 2000 N; this was close to the peak vertical force that an athlete would exert on the plate during a sprint trial (Mero & Komi, 1994). The force readings of both plates were checked for agreement by rolling the loaded wheel onto the first force plate and letting it rest for 5 s, then rolling it onto the second force plate and letting it rest for a further 5 s.
and comparing the settled readings. Collection of the test data consisted of manually rolling the loaded wheel across both plates at a near constant velocity. In total 15 test trials were collected, by rolling the wheel across the plates in three different locations.

The three paths were chosen so that one lay along the mid line of the plates, where accuracy is reported as highest (Bobbert & Schamhardt, 1990), and the other two were towards the edges of the plates, where accuracy is lower (Fig. 5.5). The trolley was drawn along different paths so that data were available relating to different sections of the force plate. It was necessary to consider the different locations on the plate due to the inherent characteristics of piezoelectric force plates, tending to increase errors in COP calculation when forces are applied towards the extremities and in particular the corners (Bobbert & Schamhardt, 1990). The force plates were reset following each trial to reduce any effects of hysteresis and to cancel amplifier drift.
Synchronised marker positional data and force plate data from both plates were collected throughout trials. Positional data were collected as x, y and z positions at each time point. Force plate data were collected via eight separate channels for each plate; the data recorded by each channel are described in the following section.

5.2.2 Verification Study Data Processing
Data processing was performed using the COP_compare (Appendix B) program written in MATLAB (R2009b, The Mathworks, USA). Data were filtered using a digital low-pass Butterworth filter with an optimal cut-off frequency determined using the autocorrelation method of Challis (1999), implemented using program autocor_CO (Appendix B). Raw force data were collected via eight channels; the contents of each channel are outlined in Table 5.1.

Table 5.1. Data recorded by each channel for each force plate.

<table>
<thead>
<tr>
<th>Output Signal</th>
<th>Channel</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>fx_{12}</td>
<td>1</td>
<td>Force in x direction measured by sensors 1 and 2</td>
</tr>
<tr>
<td>fx_{34}</td>
<td>2</td>
<td>Force in x direction measured by sensors 3 and 4</td>
</tr>
<tr>
<td>fy_{14}</td>
<td>3</td>
<td>Force in y direction measured by sensors 1 and 4</td>
</tr>
<tr>
<td>fy_{23}</td>
<td>4</td>
<td>Force in y direction measured by sensors 2 and 3</td>
</tr>
<tr>
<td>fz_{1}</td>
<td>5</td>
<td>Force in z direction measured by sensor 1</td>
</tr>
<tr>
<td>fz_{2}</td>
<td>6</td>
<td>Force in z direction measured by sensor 2</td>
</tr>
<tr>
<td>fz_{3}</td>
<td>7</td>
<td>Force in z direction measured by sensor 3</td>
</tr>
<tr>
<td>fz_{4}</td>
<td>8</td>
<td>Force in z direction measured by sensor 4</td>
</tr>
</tbody>
</table>

The locations of sensors 1 to 4 relative to the x, y and z axes of the plate are illustrated in Figure 5.6. Distances a, b and az_0 are used in the subsequent force plate equations.
Figure 5.6. Location of force plate sensors (1 to 4) relative to the centre of the force plate (Kistler Instruments Ltd., UK).

**Calculation of force and COP for data collected from one force plate**

Raw data recorded by the eight force plate channels were processed using Equations 5.1 to 5.12, provided by the force plate manufacturer, to calculate vector forces and COP for each force plate. Component forces in the x, y and z directions were calculated by summing the output of the relevant channels, such that:

\[ F_x = f_{x_{12}} + f_{x_{34}} \quad [5.1] \]

\( F_x = \text{total component force in x direction} \)
\( f_{x_{12}} = \text{component force in x direction measured by sensors 1 and 2} \)
\( f_{x_{34}} = \text{component force in x direction measured by sensors 3 and 4} \)

\[ F_y = f_{y_{14}} + f_{y_{23}} \quad [5.2] \]

\( F_y = \text{total component force in y direction} \)
\( f_{y_{14}} = \text{component force in y direction measured by sensors 1 and 4} \)
\( f_{y_{23}} = \text{component force in y direction measured by sensors 2 and 3} \)

\[ F_z = f_{z_1} + f_{z_2} + f_{z_3} + f_{z_4} \quad [5.3] \]

\( F_z = \text{total component force in z direction} \)
\( f_{z_{1-4}} = \text{component force in z direction measured by sensors 1 to 4} \)
To determine COP location, moments around the plate’s internal x and y axes were firstly calculated:

\[ M_x = b \times (f_{z1} + f_{z2} - f_{z3} - f_{z4}) \] \[ M_y = a \times (-f_{z1} + f_{z2} + f_{z3} - f_{z4}) \]

**$M_x$** = moment about x axis  
**$b$** = y distance from centre of plate to centre of sensors  
**$f_{z1-4}$** = force in z direction measured by sensors 1 to 4

Moments about the plate’s internal axes were then transformed so that they were about the track surface:

\[ M_x' = M_x + (F_y \times az_0) \] \[ M_y' = M_y - (F_x \times az_0) \]

**$M_x'$** = x moment about track surface  
**$M_x$** = moment about x axis of plate  
**$F_y$** = force in y direction  
**$az_0$** = track surface offset from centre of plate

**$M_y'$** = y moment about track surface  
**$M_y$** = moment about y axis of plate  
**$F_x$** = force in x direction  
**$az_0$** = track surface offset from centre of plate

Component COP locations were calculated from the component moments and the vertical force applied to the plate:
\[ ax = -\frac{My'}{Fz} \] \[ ay = \frac{Mx'}{Fz} \]

\( ax = \) x location of COP measured from centre of plate
\( My' = \) y moment about top surface
\( Fz = \) force in z direction

\( ay = \) y location of COP measured from centre of plate
\( Mx' = \) x moment about top surface
\( Fz = \) force in z direction

**Additional calculations for force and COP for data collected from two plates**

Component force magnitudes were calculated by summing the force measured by each plate:

\[ Fx = Fx_a + Fx_b \] \[ Fy = Fy_a + Fy_b \] \[ Fz = Fz_a + Fz_b \]

\( Fx = \) total force in x direction
\( Fx_a = \) force in x direction measured by Plate A
\( Fx_b = \) force in x direction measured by Plate B

\( Fy = \) total force in y direction
\( Fy_a = \) force in y direction measured by Plate A
\( Fy_b = \) force in y direction measured by Plate B

\( Fz = \) total force in z direction
\( Fz_a = \) force in z direction measured by Plate A
\( Fz_b = \) force in z direction measured by Plate B
COP for instances when both plates were loaded was calculated by weighting each plate’s COP based on the relative force that was applied to that plate:

\[ P_a = Fz_a / Fz \]  [5.13]

\[ P_a = \text{Plate A weighting} \]
\[ Fz_a = \text{vertical force measured by Plate A} \]
\[ Fz = \text{total vertical force measured by both plates} \]

\[ P_b = Fz_b / Fz \]  [5.14]

\[ P_b = \text{Plate B weighting} \]
\[ Fz_b = \text{vertical force measured by Plate B} \]
\[ Fz = \text{total vertical force measured by both plates} \]

Global COP location in the x and y directions was then calculated by combining the values calculated from each plate with the plate weighting values:

\[ ax = (ax_a \times P_a) + (ax_b \times P_b) \]  [5.15]

\[ ax = \text{global x location of COP} \]
\[ ax_a = \text{x location of COP measured by Plate A} \]
\[ ax_b = \text{x location of COP measured by Plate B} \]
\[ P_a = \text{Plate A weighting} \]
\[ P_b = \text{Plate B weighting} \]

\[ ay = (ay_a \times P_a) + (ay_b \times P_b) \]  [5.16]

\[ ay = \text{global x location of COP} \]
\[ ay_a = \text{y location of COP measured by Plate A} \]
\[ ay_b = \text{y location of COP measured by Plate B} \]
\[ P_a = \text{Plate A weighting} \]
\[ P_b = \text{Plate B weighting} \]
Verification of COP measured across two force plates

The three markers attached to the trolley formed a triangle on the trolley’s top surface (Fig. 5.7). The locations of these markers were combined to calculate the triangle’s centre, referred to as the ‘control point’. The COP location and the position of the control point were corrected for any lateral motion of the trolley by adjusting the vectors connecting each point to the global origin so that they lay on the y axis (Fig. 5.7).

![Diagram of trolley and force plates](image)

(a)

![Diagram of control point and COP separation](image)

(b)

Figure 5.7. Location of control point and COP before adjustment (a) and after adjustment (b) and the separation between adjusted COP and control point ($y_s$).

The adjusted locations were calculated using trigonometric equations. The distance between the adjusted control point location and the adjusted COP location was calculated throughout each trial. The mean distance between the two adjusted points was calculated whilst the trolley was stationary and resting on one plate; this value was used as a stationary reference value with which to compare the dynamic trials.

5.2.3 Verification Study Results and Discussion

Mean error results for COP calculations are presented in Table 5.2. The largest mean difference between adjusted COP and adjusted control points was observed when the trolley was rolled along the middle of the force plates; however, the
standard deviation across all five trials was lowest for this position indicating low variability. The consistency of the results for the middle position was expected as force plate accuracy for COP calculation decreases towards the extremities of the plate, with the corners containing the greatest amount of error (Bobbert & Schamhardt, 1990). The mean error for all trials was 0.0027 m, whilst the largest error (0.0076 m) occurred in a trial on the right side of the plate.

Table 5.2. Mean [±SD] difference between adjusted COP and control points for three locations tested.

<table>
<thead>
<tr>
<th>Lateral Position</th>
<th>Mean Difference (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0006 [0.0040]</td>
</tr>
<tr>
<td>2</td>
<td>0.0054 [0.0009]</td>
</tr>
<tr>
<td>3</td>
<td>0.0014 [0.0055]</td>
</tr>
</tbody>
</table>

Example locations of adjusted COP and the control point from one trial are shown in Figure 5.8. The curves show the distance of the COP and control point from the origin throughout the trial and the high agreement between the two. Comparison between the shaded and un-shaded areas of the curves shows the similarity in COP calculation when using one plate and a combination of two plates.

Figure 5.8. Example comparison of adjusted COP and adjusted control point, the shaded area indicates the section used for analysis (±0.05 m from mid-point between plates).
The difference between the two curves presented in Figure 5.8 was consistent throughout the trials. A similar difference was observed in the shaded ‘crossover’ region as the wheel moved from Plate A to Plate B (~1.125 to ~1.375 s) to the ‘static’ section when the wheel was located on Plate A (between 0 and ~0.75 s).

To determine the effect of COP error on subsequent IDA calculations, power data from a trial sprint run were calculated using the measured COP, using the inverse dynamic equations detailed in section 5.3.4 of this chapter. The analysis was then repeated having altered the COP values by 0.0027 and 0.0076 m, which is the mean and maximum errors calculated in the verification study, respectively. Root mean squared difference (RMSD) values were calculated between the results calculated with the measured and altered COP values. RMSD values were normalised as percentage values by dividing by the range of power values for each joint and multiplying the result by 100. Table 5.3 includes sensitivity results for the joint power calculations based on error caused by calculating COP across two force plates. The largest effect was seen at the knee joint (1.47 and 4.02%) whilst the smallest effect was for the ankle joint (0.27 and 0.73%). These results are similar in magnitude to those reported for other inverse dynamic sensitivity analyses, such as that of Bezodis et al. (2008), who reported possible error values in joint power caused by error introduced in the digitising process. As COP error is a position error, it is directly comparable to error introduced by the digitising process.

Table 5.3. Effect of mean and maximum error in COP location on the calculation of joint power for the ankle, knee and hip joints.

<table>
<thead>
<tr>
<th>COP Error</th>
<th>Effective Change in Joint Power (%RMSD)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ankle</td>
<td>Knee</td>
<td>Hip</td>
</tr>
<tr>
<td>Mean*</td>
<td>0.27</td>
<td>1.47</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>Max**</td>
<td>0.73</td>
<td>4.02</td>
<td>1.06</td>
<td></td>
</tr>
</tbody>
</table>

*0.0027 m **0.0076 m
5.2.4 Summary of Verification Study

Two questions were posed in the introduction to this verification study. The answers to these questions will determine the suitability of using COP data from foot contacts occurring across two force plates. These answers are:

5. **How accurate is COP calculation for data collected using two force plates?**
   Mean error in COP location during contact between two force plates was 0.0027 m. COP calculation displayed greater consistency for contacts occurring towards the middle of the plates’ x axis than those towards the edge.

6. **What effect does error in COP calculation have on power values calculated using IDA?**
   The effects of the mean COP error on net joint power at the ankle, knee and hip joints were calculated. Results of the joint power sensitivity analysis indicated that an error of 0.0027 m would lead to a change in joint power ranging from 0.27% for the ankle to 1.47% for the knee.

The results of the verification study indicate that it is acceptable to use foot contacts that occur across two force plates as an input for IDA. It is important to note that for a contact across two plates, a significant amount of the contact is likely to occur outside of the force plates’ sensors, where the greatest amount of error occurs. In conclusion, whilst foot contacts occurring in the centre of the plate are favourable as they are likely to contain the least amount of error, foot contacts that occur across two plates still contain an acceptable amount of error. Therefore it was decided that the use of foot contacts occurring across two force plates was acceptable and this method was used for the collection of kinetic data for this chapter.

5.3 Method

5.3.1 Participants

Eight athletes participated in the kinetic asymmetry study. The University Research Ethics Committee was consulted prior to data collection, who granted ethical approval for the study. Athletes gave written informed consent to participate in the study (Appendix A.6) and parental consent was obtained for Athletes 9 and
10, who were under 18 years of age. All eight athletes had also participated in the kinematic study described in Chapter 4, giving insight into their kinematic asymmetry. Athlete profiles are presented in Table 5.4. Individual athlete numbers were maintained between the kinematic analysis presented in Chapter 4 and the kinetic analysis presented within this chapter for ease of comparison between kinematic and kinetic results for each athlete. Two athletes (Athletes 7 and 8) that were included in the kinematic asymmetry study presented in Chapter 4 were not included in the analysis of kinetic asymmetry. These athletes were excluded from the kinetic analysis due to larger inconsistency in their foot placements relative to the other athletes, resulting in less than two acceptable foot contacts with the force plates for either the left or right foot.

Table 5.4. Athlete profiles of physical characteristics and personal best (PB) times.

<table>
<thead>
<tr>
<th>Athlete #</th>
<th>Height (m)</th>
<th>Mass (kg)</th>
<th>Age (years)</th>
<th>Event</th>
<th>PB (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>1.74</td>
<td>73.7</td>
<td>25</td>
<td>100 m</td>
<td>11.00*</td>
</tr>
<tr>
<td>02</td>
<td>1.81</td>
<td>78.3</td>
<td>21</td>
<td>100 m</td>
<td>10.67*</td>
</tr>
<tr>
<td>03</td>
<td>1.80</td>
<td>74.6</td>
<td>30</td>
<td>100 m</td>
<td>11.20*</td>
</tr>
<tr>
<td>04</td>
<td>1.79</td>
<td>67.9</td>
<td>24</td>
<td>400 m</td>
<td>50.65***</td>
</tr>
<tr>
<td>05</td>
<td>1.84</td>
<td>82.9</td>
<td>22</td>
<td>100 m</td>
<td>11.39*</td>
</tr>
<tr>
<td>06</td>
<td>1.86</td>
<td>85.2</td>
<td>21</td>
<td>100 m</td>
<td>10.86*</td>
</tr>
<tr>
<td>09</td>
<td>1.81</td>
<td>71.6</td>
<td>16</td>
<td>200 m</td>
<td>23.80**</td>
</tr>
<tr>
<td>10</td>
<td>1.65</td>
<td>57.7</td>
<td>15</td>
<td>200 m</td>
<td>23.80**</td>
</tr>
</tbody>
</table>

PB times relate to: * 100 m, ** 200 m and *** 400 m.

5.3.2 Data Collection

Force and positional data were collected at the National Indoor Athletics Centre in Cardiff. A CODA cx1 motion analysis system (Charnwood Dynamics, Leicester, UK) was utilised, operating four scanners at a sampling rate of 200 Hz. Scanners were positioned with their mid points raised to a height of 1.30 m above the track surface. The scanners were located in pairs, 4.20 m from the centre of the running lane, at a separation of 4.00 m along the lane (Fig. 5.9).

The equipment setup resulted in a bilateral field of view of approximately 8.20 m along the lane. The data capture area was centred 45.00 m from the start of each run, allowing athletes to fully accelerate. All cables were located away from the
running lane where possible and those that had to cross the running lane were suspended above the lane so that they did not cause interference with the athlete’s running pattern, as described in Section 3.1.2.1. Two force plates (Kistler 9287BA) were located within the field of view and connected, via independent control boxes (Kistler, 5233a), to the CODA hub. The force plates were placed end to end, with the first plate located 44.10 m from the athletes’ start line. Both force plates were mounted in customised parallel housings and covered with running track (Mondo, USA) identical to that which covered the rest of the lane.

![Diagram showing the location of force plates and CODA scanners](image)

Figure 5.9. Location of force plates and CODA scanners for kinetic data collection, the shaded area indicates the field of view of the CODA scanners.

The CODA system was aligned according to the manufacturer’s guidelines. Alignment involved placing three markers on the track surface so that they formed two perpendicular vectors representing the x and y axes, intercepting at the origin. The x, y and z axes were defined as the medio-lateral, antero-posterior and vertical axes, respectively and were positioned so that they were parallel to the corresponding axes of the force plates. Athletes were tracked using twelve active CODA markers. The markers were connected in pairs to ‘twin-marker drive boxes’ and attached prior to testing. Markers and drive boxes were attached to the
athletes using adhesive tape. Markers were located lateral to the fifth metatarsal-phalangeal joint, lateral malleolus, lateral condyle of the tibia, greater trochanter, iliac crest and greater tubercle for both sides of the body (as detailed in the Chapter 4, Fig. 4.2).

Athletes all performed their own warm-up under the guidance of their coach. Coordinates of marker positions were collected whilst athletes performed 60 m sprint runs. Athletes were instructed to run maximally, through the data collection area, to a finish line located 6.70 m afterwards. Furthermore, athletes were instructed not to target the force plates and to focus on the finish line, as if they were performing in competition. The CODA system was triggered manually following athletes’ first movements from their starting position; this initiated the collection of both force and kinematic data. Both force plates were reset following each trial to negate any hysteresis or drift effects. Six athletes (Athletes 1 to 6) performed twelve trials over two separate sessions. The remaining two athletes were available for one session and performed nine runs in that session.

Trials were rejected if either foot did not contact the force plates, if the foot contact overlapped the plate boundaries (excepting overlap between the two plates) or if the athlete noticeably altered their running style to target the force plate. Halfway through each session, the start mark was repositioned by one step length to allow collection of force data from the contralateral foot. Force data were collected for a minimum of three trials per foot for each athlete, with a group average of five successful contacts per foot. Recovery time between trials was self-selected and typically lasted for approximately 10 minutes. Step velocity was compared for trials completed in separate sessions by the same athlete to check that there were no significant \((p<0.05)\) inter-session differences (Appendix A.3) before data were pooled for each athlete.

5.3.3 Data Processing
Data were processed using the kinetic_asym program (Appendix B) written in MATLAB (R2010a, The Mathworks, USA). Ground reaction force data along the \(y\) and \(z\) axes were filtered by way of a fourth order low-pass Butterworth filter. Cut-off frequencies were calculated for each trial using the autocorrelation method (Challis, 1999) based on 0.1 Hz steps in cut-off frequency ranging from 1 to 495
Hz. Typical cut-off frequency for the force data was ~180 Hz. The autocorrelation procedure was implemented via the autocor_CO program (Appendix B).

Instants of TD and TO were determined from the vertical force data, having established a contact threshold for each trial. The contact threshold was defined as the mean value plus two standard deviations of the unloaded force plate, as used in similar previous studies (Bezodis et al., 2008). This threshold value was chosen as it represents 95% of the area under a normal curve (Vincent, 2005), therefore giving 95% confidence in the detection of TD and TO. TD was defined as the first epoch when the force measurement exceeded the threshold value and TO was the first epoch after TD when the force measurement returned below the threshold value.

Because of the dominance of sagittal plane movements in sprint running discussed in Chapter 2, two-dimensional data from this plane were analysed (Bezodis et al., 2008; Johnson & Buckley, 2001). Sagittal plane coordinates were extracted from the three-dimensional marker coordinates and used for all further calculations. An interpolating cubic spline was utilised to replace marker data for sections when markers became occluded. Occluded data were identified using the internal logical ‘in-view’ variable generated by the CODA system during data collection. Occlusion was caused by markers being obscured from the view of the CODA scanners, such as when a hand passed in front of hip and iliac markers; this typically obscured the marker for approximately six epochs (0.030 s).

Marker positional data along with force data used as IDA inputs were filtered using the same within trial cut-off frequencies. Use of different cut-off frequencies for kinetic and kinematic inverse dynamic analysis inputs can result in false peaks in the calculated joint moments due to the different frequencies of noise being removed from different inputs (Bisseling & Hof, 2006). Cut-off frequencies for inverse dynamic input data were determined for each trial via the autocorrelation method (Challis, 1999) performed on the kinematic data. Prior to filtering, kinetic data required as an input for the inverse dynamic analysis were downsampled to 200 Hz, with each sample corresponding to an epoch of kinematic data. All velocities and accelerations required as IDA inputs were calculated via the gradient function in MATLAB (The Mathworks, USA). 2D joint angles were
calculated for left and right sides of the body in the sagittal plane. Joint angles were calculated using the cosine rule as described in Chapter 4, section 4.2.4.1.

5.3.4 Inverse Dynamics Analysis
A two-dimensional IDA, as presented by Winter (2009), was employed to calculate resultant moments acting at each of the three joints of each leg during the sprint trials. A toe-up method was undertaken using the resultant forces measured by the force plate. Force data, including the location of COP, were combined with the kinematic marker data and inertia data calculated from the segment weightings proposed by de Leva (1996), with the exception of the foot segment, for which values from Dempster’s (1955) model were utilised. A mass representative of a standard sprinting shoe (0.20 kg) was added to the foot segment, as recommended by Hunter et al. (2004b).

Reaction forces acting at each joint were calculated using Equation 5.17:

\[ \sum F = m \cdot a \]  

\[ F = \text{force acting on segment} \]
\[ m = \text{mass of segment} \]
\[ a = \text{acceleration of segment} \]

A free body diagram was used to summarise the forces acting on the \( i^{\text{th}} \) segment (Fig. 5.10). Forces acting on each segment were calculated from the mass and acceleration of the segment, combined with the force transferred from the previous segment.
Figure 5.10. Free body diagram of the \( i^{th} \) segment of the leg, used to summarise joint reaction forces.

Horizontal and vertical forces acting on each joint were calculated from the ground up in a distal to proximal method (Equations 5.18 and 5.19). The initial force inputs were the GRF values measured by the force plates.

\[
F_{y_i} = m \cdot a_y - F_{y_{i-1}} \quad [5.18]
\]

\( F_{y_i} \) = horizontal force acting on \( i^{th} \) joint  
\( m \) = mass of \( i^{th} \) segment  
\( a_y \) = horizontal acceleration of \( i^{th} \) segment  
\( F_{y_{i-1}} \) = horizontal force acting on \( i-1^{th} \) segment

\[
F_{z_i} = m \cdot a_z - F_{z_{i-1}} + m \cdot g \quad [5.19]
\]

\( F_{z_i} \) = vertical force acting on \( i^{th} \) joint  
\( m \) = mass of \( i^{th} \) segment  
\( a_z \) = vertical acceleration of \( i^{th} \) segment  
\( F_{z_{i-1}} \) = vertical force acting on \( i-1^{th} \) segment  
\( g \) = acceleration due to gravity

Resultant joint moments for the \( i^{th} \) segment were calculated as the product of the moment of inertia and angular acceleration of the segment:
\[ \sum M = I \cdot \alpha \]  

\[ M = \text{resultant joint moment of } i^{th} \text{ segment} \]
\[ I = \text{moment of inertia of } i^{th} \text{ segment} \]
\[ \alpha = \text{angular acceleration of } i^{th} \text{ segment} \]

A second free body diagram (Fig. 5.11) was utilised to summarise the moments acting at each end of the \( i \)th segment.

Figure 5.11. Free body diagram of the \( i \)th segment of the leg, used to summarise joint moments.

The IDA equation (Equation 5.21) was used to calculate resultant joint moments around the \( i \)th segment’s centre of mass:

\[ M_{i-1} + M_i + (F_{z_{i-1}} \cdot dy) + (F_{y_{i-1}} \cdot dz) - (F_{z_i} \cdot py) - (F_{y_i} \cdot pz) = I \cdot \alpha \]  

\( M_{i-1} = \text{resultant joint moment acting on } i-1^{th} \text{ joint} \)
\( M_i = \text{resultant joint moment acting on } i^{th} \text{ joint} \)
\( F_{z_{i-1}} = \text{resultant vertical force acting on } i-1^{th} \text{ joint} \)
\( dy = \text{horizontal distance from distal end of segment to centre of mass} \)
\( F_{y_{i-1}} = \text{resultant horizontal force acting on } i-1^{th} \text{ joint} \)
dz = vertical distance from distal end of segment to centre of mass
$F_{z_i}$ = resultant vertical force acting on $i^{th}$ joint
$py$ = horizontal distance from proximal end of segment to centre of mass
$F_{y_i}$ = resultant horizontal force acting on $i^{th}$ joint
$pz$ = vertical distance from proximal end of segment to centre of mass
$l$ = moment of inertia of $i^{th}$ segment
$\alpha$ = angular acceleration of $i^{th}$ segment

A functional definition of joint angles was used (Fig. 5.12), with extension defined as positive at all joints. The same positive definition was used for the calculation of joint moments.

![Figure 5.12](image)

Figure 5.12. Analysed segments of the lower limb, including positive definition of joint angles.

Winter’s (1980) definition of support moment was used to sum the individual joint moments of the lower limb (Equation 5.22):

$$M_S = M_A + M_K + M_H$$  \[5.22\]

$M_S = support$ moment
$M_A = net$ moment acting at the ankle joint
$M_K = net$ moment acting at the knee joint
\[ M_H = \text{net moment acting at the hip joint} \]

Joint power was calculated at the ankle, knee and hip joints as the product of the resultant joint moment and the joint angular velocity:

\[ P = M \cdot \omega \quad [5.23] \]

\[ P = \text{resultant joint power} \]
\[ M = \text{resultant joint moment} \]
\[ \omega = \text{joint angular velocity} \]

Net joint work was calculated as the integral of the power at each joint with respect to time:

\[ W_j = \int_{t_1}^{t_2} P_j dt \quad [5.24] \]

\[ W_j = \text{joint work} \]
\[ P_j = \text{resultant joint power} \]
\[ t_1 = \text{time of start of joint power phase} \]
\[ t_2 = \text{time of end of joint power phase} \]

Joint moment, power and work values were normalised for individual athlete’s body mass and height using the method of Hof (1996). Joint moment and work values were divided by each athlete’s BW and height. Joint power was divided by body mass, gravitational acceleration \((g^{3/2})\) and height \((h^{1/2})\). This normalisation procedure resulted in joint kinetic results being dimensionless and also allowed for direct comparison of values between different athletes.

5.3.5 Data analysis

_Calculation of variables_

Seven discrete variables were selected for analysis. These variables were chosen based on either their mechanical influence on the kinematic variables analysed in Chapter 4 or being advocated by previous kinetic sprint research. Table 5.5 shows
the variables that were used for this study, along with their justification for inclusion. All variables were calculated throughout the contact phase. The discrete variables analysed were net horizontal (IMP_\text{H}) and vertical (IMP_\text{V}) impulses, maximum vertical force (Fz_{\text{MAX}}), mean support moment (M_{\text{SUP}}) and net work performed at the ankle (WA_{\text{NET}}), knee (WK_{\text{NET}}) and hip (WH_{\text{NET}}) joints.

Table 5.5. Discrete kinetic variables selected for asymmetry analysis.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMP_\text{H}</td>
<td>Horizontal impulse</td>
<td>Result of y_{TD}, which displayed asymmetry in Chapter 4</td>
</tr>
<tr>
<td>Fz_{\text{MAX}}</td>
<td>Maximum vertical force</td>
<td>Inclusion in kinetic analyses of sprinting (Belli \textit{et al}., 2002; Bezodis \textit{et al}., 2008)</td>
</tr>
<tr>
<td>IMP_\text{V}</td>
<td>Vertical impulse</td>
<td>Provides additional information into the vertical force production throughout stance, influencing Fz_{\text{MAX}}</td>
</tr>
<tr>
<td>M_{\text{SUP}}</td>
<td>Mean support moment</td>
<td>Related to zH_{\text{MIN}}, which displayed asymmetry in Chapter 4, also provides measure of overall limb asymmetry (Winter, 1980)</td>
</tr>
<tr>
<td>WA_{\text{NET}}</td>
<td>Net ankle work</td>
<td>Inclusion in kinetic analyses of sprinting (Belli \textit{et al}., 2002; Bezodis \textit{et al}., 2008). Also related to angular measures in Chapter 4.</td>
</tr>
<tr>
<td>WK_{\text{NET}}</td>
<td>Net knee work</td>
<td></td>
</tr>
<tr>
<td>WH_{\text{NET}}</td>
<td>Net hip work</td>
<td></td>
</tr>
</tbody>
</table>

To allow comparison of the differences between mean left and right values for different variables, all discrete results were normalised as a percentage of the maximum value measured for either side of the body for each athlete:

\[ X_{\text{NORM\_SIDE}} = \frac{X_{\text{MEAN\_SIDE}}}{\text{MAX}(X_{\text{BOTH}})} \times 100\% \]  \[5.25\]

- \( X_{\text{NORM\_SIDE}} \) = normalised value for specific side
- \( X_{\text{MEAN\_SIDE}} \) = mean un-normalised value for specific side
- \( \text{MAX}(X_{\text{BOTH}}) \) = maximum un-normalised value of both sides
Statistical analysis

Kinetic results were tested for normality using the criteria of Peat and Barton (2005). First, if the difference between the mean and median values for each athlete was ≤10%, the data were accepted as displaying a normal distribution. Any data that did not satisfy the first test then had to breach two out of four additional tests to be considered as having a non-normal distribution. These additional tests were: 1. the mean and standard deviation test, checking whether the magnitude of two standard deviations of the data was less than the mean value; 2. a Shapiro-Wilks test for normality; 3. skewness and kurtosis statistics being less than 1 and 4. the result of skewness or kurtosis divided by standard error being ≤1.96.

All statistical tests were performed using SPSS version 17.0 (Chicago, USA). Using the criteria of Peat and Barton (2005), all variables were accepted as displaying a normal distribution; therefore, parametric statistical tests were subsequently employed. Paired-samples t-tests were utilised to determine the significance of differences in normalised results from left and right sides of the body for each athlete. All t-test results were interpreted at the 95% confidence level, using an alpha level of 0.05 (Vincent, 2005).

Event asymmetry score

The event asymmetry score was calculated from variables measured at specific events during contact. A t-test was utilised to test for significant differences at the 0.05 confidence level between left and right values of discrete data. Each variable was assigned a significance weighting of either 1 or 0 based on the results of the t-tests, with 1 indicating a significant difference and 0 indicating no difference. Absolute symmetry angle (ABS\(\theta\)\text{SYM}) values were calculated between mean left and right values using an adaptation of the equation presented by Zifchock et al. (2008b):

\[
ABS\theta_{SYM} = \left[45^\circ - \frac{\arctan(X_{left}/X_{right})}{90^\circ}\right] \times 100\%
\]  

ABS\(\theta\)\text{SYM} = absolute symmetry angle

\(X_{left} = \text{mean value for the left side}\)

\(X_{right} = \text{mean value for the right side}\)
The ABSθ<sub>SYM</sub> score for each variable was multiplied by the significance weighting so that only variables displaying a significant difference between sides were included in the kinetic asymmetry score. The event asymmetry score for each athlete was calculated by summing the results of each variable’s ABSθ<sub>SYM</sub> multiplied by its significance weighting.

**Profile asymmetry score**

The profile asymmetry score considered continuous data to provide greater insight into the interactions of the ankle, knee and hip joints during the entire duration of stance. Joint power-time was chosen for the continuous comparison based on the recommendation of Sadeghi et al. (2000), due to the inclusion of both force and movement occurring around the joints. Profile asymmetry scores were calculated on an individual athlete basis. Joint power profiles at the ankle, knee and hip joints were normalised to 100% of stance by interpolating the power profiles of each trial to 101 equally spaced points. Interpolation was implemented via an interpolating spline function in MATLAB (R2010a, The Mathworks, USA). Mean and standard deviations were then calculated for the joints of the left and right limbs. Calculation of the profile asymmetry score comprised four characteristics of the power curves; these were the phase, magnitude, time and overall difference of each curve.

Phase difference was calculated using the concept presented by Crenshaw and Richards (2006). Firstly, RMSD was calculated between the mean power curves for the left and right side, for all 101 points. One curve was then shifted in 1% increments so that sample 100 became sample 1, sample 1 became sample 2 and so on. RMSD was recalculated following each shift and phase shift was quantified as the number of shifts taken to minimise the RMSD value (Fig. 5.13).
Figure 5.13. Example left (red) and right (green) mean power curves for the ankle joint during stance both before phase shift (a) and after optimal phase shift (b).

Asymmetry of the magnitude and time of the power curves was calculated by comparing minimum and maximum power values and the duration of each curve (CT). For minimum values, maximum values and CT, $ABS\theta_{SYM}$ was calculated between the mean values of all trials for the left and right sides. $ABS\theta_{SYM}$ values were then multiplied by 1 or 0 depending on whether there was a significant ($p<0.05$) difference between the values of each side.

The final element of the profile analysis considered the magnitude of the entire power curves. A t-test was performed on each of the 101 points of the power profiles, with each point assigned a significance weighting of either 1 (significant) or 0 (non-significant) depending on the t-test results set at an alpha level of 0.05. An overall value was calculated for each joint by summing the significance weightings for all points.

**Kinetic asymmetry score**

A kinetic asymmetry score (KAS) was assigned to each athlete by summing the event and profile asymmetry scores. KAS results (mean=110.05) were approximately ten times larger than KMAS results (mean=11.27) calculated in Chapter 4. To allow comparisons between the two scores, KAS were divided by ten so that they were of similar magnitude to the KMAS. The same adjustment was applied to each KAS, so that the rank order of the athletes’ asymmetry scores was not affected.
5.4 Results

Kinetic asymmetry results are presented in the following section. There are three main parts to the results section; mean kinetic event data, kinetic asymmetry profiles and power profile comparisons.

Table 5.6 contains KAS values for each athlete. Scores ranged from 6.25 for Athlete 6 to 28.67 for Athlete 2. Athletes 4, 5, 6 and 9 had similar KAS values separated by 1.11, whilst the remaining four athletes displayed larger values over a greater range. Also included are the event asymmetry scores and the individual contributors to the profile asymmetry scores. Individual contributors to event asymmetry scores are detailed in the subsequent figure (Fig. 5.14).

Mean kinetic event values for all athletes are presented in Appendix A.5 (Table A.4). Net work values at all three joints were close to zero for some athletes (e.g. Athlete 5 left ankle, Athlete 4 left knee, Athlete 10 left hip), this led to ABSθSYM values that approached 50%. Many athletes’ net work values for the knee joint were opposite in polarity for the left and right side, this allowed ABSθSYM values to increase above 50% and approach the theoretical maximum of 100% for some athletes (e.g. Athletes 2 and 10).

Figure 5.14 shows kinetic asymmetry profiles for each athlete. The top section of each figure illustrates the ABSθSYM for each kinetic event variable. The bottom section of each figure shows normalised mean kinetic event results for left and right foot contacts for all variables. Also indicated on the figures are the results of the t-test, with an asterisk indicating that there was a significant difference (p<0.05) between sides. The bottom sections of Figures 5.14a to h reinforce the finding that only net work values exhibited differences in polarity between sides, leading to the largest ABSθSYM values. Of the remaining kinetic variables displayed in Figure 5.14, net horizontal impulse demonstrated the largest asymmetry with ABSθSYM values in excess of 10% for Athletes 1, 3, 4 and 9. The largest ABSθSYM value of all athletes was 93% for the net ankle work of Athlete 10; however, this difference was not significant. The largest significant asymmetry was 77% for the net knee work of Athlete 2.
Table 5.6. Individual athlete KAS results. Also included are individual contributions to the profile asymmetry score for the ankle (A), knee (K) and hip (H) joints and the total event asymmetry score for athlete.

<table>
<thead>
<tr>
<th>Athlete</th>
<th>KAS</th>
<th>Event Asymmetry Score</th>
<th>Phase Difference (%)</th>
<th>Profile Asymmetry Score (%)</th>
<th>Contact Time (%)</th>
<th>Overall Magnitude (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>A  K  H</td>
<td>A  K  H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>19.35</td>
<td>68.61</td>
<td>8  8  4</td>
<td>8.43 0.00 3.46</td>
<td>0.00</td>
<td>66 23 4</td>
</tr>
<tr>
<td>2</td>
<td>28.67</td>
<td>76.94</td>
<td>4  12 14</td>
<td>7.12 17.92 16.72</td>
<td>0.00</td>
<td>19 69 50</td>
</tr>
<tr>
<td>3</td>
<td>17.32</td>
<td>13.99</td>
<td>2  0 10</td>
<td>5.21 31.04 18.92</td>
<td>0.00</td>
<td>20 34 38</td>
</tr>
<tr>
<td>4</td>
<td>7.36</td>
<td>24.58</td>
<td>0  8 16</td>
<td>5.01 0.00 0.00</td>
<td>2.03</td>
<td>12 6 0</td>
</tr>
<tr>
<td>5</td>
<td>6.96</td>
<td>29.12</td>
<td>2  0 0</td>
<td>9.49 0.00 0.00</td>
<td>0.00</td>
<td>17 0 12</td>
</tr>
<tr>
<td>6</td>
<td>6.25</td>
<td>14.54</td>
<td>2  20 4</td>
<td>0.00 0.00 0.00</td>
<td>0.00</td>
<td>14 8 0</td>
</tr>
<tr>
<td>9</td>
<td>6.93</td>
<td>41.25</td>
<td>2  6 0</td>
<td>0.00 0.00 0.00</td>
<td>0.00</td>
<td>7 5 8</td>
</tr>
<tr>
<td>10</td>
<td>12.29</td>
<td>55.27</td>
<td>2  0 0</td>
<td>0.00 0.00 37.65</td>
<td>0.00</td>
<td>14 2 12</td>
</tr>
</tbody>
</table>
Figure 5.14. Kinetic asymmetry profiles for all athletes. * indicates significant difference between mean left and right values.
Joint power profiles

Figure 5.15 shows mean [±SD] power curves of the ankle, knee and hip joints for the left and right limbs during stance. The ankle profile displayed the greatest consistency, as indicated by the magnitude of the standard deviations compared to those for the knee and hip joints. The shape of the power curves for the ankle joints were the most consistent between athletes, they also displayed the largest range of power values compared to the knee and hip joints.

The knee joint power profiles followed a similar pattern during mid-stance for most athletes, with larger differences between the left and right sides seen towards the beginning (e.g. Fig. 5.15 (b)) and end (e.g. Fig. 5.15 (h)) of the stance phase. Larger standard deviations for this joint for all athletes indicated less consistency than was observed at the ankle joint.

The largest intra-athlete differences, shown by the large standard deviations, were observed for the power profiles of the hip joint (e.g. Fig. 5.15 (l)). Most hip profiles showed an extensor power phase through the majority of stance followed by a small flexor power phase towards the end of stance. A large difference in the power phases of the left and right sides was displayed by Athlete 10 during the final 20% of stance (Fig. 5.15 (x)), with the polarity of the power being opposite for the left and right sides. Another occurrence of conflicting power polarity was observed for Athlete 5 during approximately 0 to 30% of stance (Fig. 5.15 (o)).
Figure 5.15. Mean [± SD] (dashed lines) power profiles for left (black) and right (grey) ankle, knee and hip joints. Power values are presented both un-normalised (left axes) and normalised (right axes).
Figure 5.14. Mean [± SD] (dashed lines) power profiles for left (black) and right (grey) ankle, knee and hip joints. Power values are presented both un-normalised (left axes) and normalised (right axes).
Figure 5.14. Mean [± SD] (dashed lines) power profiles for left (black) and right (grey) ankle, knee and hip joints. Power values are presented both un-normalised (left axes) and normalised (right axes).
Figure 5.16 shows the interaction between kinematic and kinetic asymmetry scores for each athlete. No conclusive trend was seen across all athletes; for example, the kinetic scores for Athletes 4 (7.36) and 9 (6.93) were similar, whereas the kinematic scores for these athletes were the highest (27.60) and lowest (4.52) of the group, respectively. Conversely, Athletes 2 and 6, who displayed the largest (28.67) and smallest (6.25) kinetic asymmetry, had kinematic scores of 10.73 and 9.86, respectively.

![Figure 5.16](image_url)

Figure 5.16. Comparison of kinematic and kinetic asymmetry scores for each athlete, athlete numbers are shown on the figure.

*Individual athlete results*

**Athlete 1**

Athlete 1 displayed the second largest KAS of the group (19.35). The largest contributor to the KAS was the significant difference between the left and right power profiles of the ankle, with a value of 66%. This value reduced to 23% for the knee joint and 4% for the hip. The event asymmetry score (69) for Athlete 1 was the second largest of the group, with net ankle work asymmetry contributing the most to this score.
**Athlete 2**
The athlete that demonstrated the greatest amount of kinetic asymmetry was Athlete 2. The most asymmetrical kinetic event variable was net work performed at the knee joint, for which $\theta_{sym}$ was 77%. The large kinetic asymmetry score for Athlete 2 was also caused by large scores in the profile asymmetry calculations, which were the result of both phase differences and differences in maximum and minimum values. Power phase differences were largest for the knee and hip joints, with the left knee displaying a 12% lag and the right hip exhibiting a 14% lag compared to the contralateral limbs.

**Athlete 3**
The KAS reported for Athlete 3 (17.32) was the third largest of the group. Comparison of the power profiles highlighted a 10% lag in the hip phase of the right leg. Differences were large in the peak negative power values for the knee and hip joints, which led to the Athlete 3 displaying the greatest asymmetry for power magnitude (55%). There were large differences in the power profiles of the knee joint at the beginning and end of stance, with the profiles showing more agreement between approximately 20 and 60% of stance. The ankle joint showed the lowest percentage of significant difference in the power profiles (20%); values were similar for the knee (34%) and hip (38%) joints.

**Athlete 4**
Athlete 4 displayed the fourth lowest KAS (7.36). The largest power phase difference was seen at the hip joint, with a lag of 16% displayed in the right leg. The knee joint showed half as much lag (8%) but with the delay occurring in the left leg. The phase difference for the ankle joint was zero. Conversely, the ankle joint displayed the largest significant difference between left and right power throughout stance (12%), compared with 6% for the knee joint and 0% for the hip joint.

**Athlete 5**
Athlete 5’s KAS of 6.96 was the third lowest. The significant difference between left and right power profiles was greatest for the ankle (17%), with a value of zero for the knee joint and 12% reported for the hip. The event asymmetry score contributed to the overall KAS with a value of 29%, this was principally due to
asymmetry in the work done at the knee joint. The phase difference in joint power profiles was low for all three joints for Athlete 5, with a value of 2% for the ankle joint and zero reported for the knee and hip joints.

**Athlete 6**

The KAS for Athlete 6 (6.25) was the lowest of the group. The largest contributor to the KAS was the phase difference for the knee power profiles (20%); this value was much lower for the ankle (2%) and hip (4%) joints. The significant difference between left and right power profiles was largest for the ankle joint (14%), with a value of 8% reported for the knee joint and zero for the hip joint.

**Athlete 9**

Athlete 9 had a KAS of 6.93, which was the second smallest in the group. There was no significant difference in the magnitude of the power values for left and right limbs for any of the three joints analysed. Phase differences were low compared to athletes with values of 2% for the ankle, 6% for the knee and 0% for the hip. The event asymmetry score for Athlete 9 was 41%; this was entirely due to asymmetry observed in the net work performed at the ankle.

**Athlete 10**

Athlete 10 had a KAS of 12.29, which was the fourth largest of the group. The event asymmetry score for Athlete 10 was 55%, which was largely due to asymmetry in the net work performed at the hip joint (45%). Power differences were almost entirely due to differences in magnitude rather than phase, with the ankle joint displaying a phase difference of 2% and the knee and hip displaying no phase difference.

### 5.5 Discussion

The aim of this study was to investigate the kinetic asymmetry of the lower limbs during sprint running, in light of the kinematic asymmetry reported in Chapter 4. Therefore, the kinetic results presented in the previous section will be discussed as individual athlete comparisons between sides and comparing the observed kinetic asymmetry with the kinematic asymmetries reported in Chapter 4.
5.5.1 General Inverse Dynamics Observations

There was agreement between many of the kinetic results calculated in this study and those calculated for different athletes in previous studies. This agreement indicates that the athletes analysed were representative of sprinters that have been analysed by other authors.

Ankle

General results indicated that there was more consistency in the kinetics of the ankle than the hip and particularly the knee. Comparison of the ankle power showed consistency in the profiles of all athletes, with a plantar flexor power absorption phase lasting for approximately 50% of stance followed by a power generation phase of similar duration. The ankle power profiles were similar to those presented in previous studies (Belli et al., 2002; Bezodis et al., 2008; Johnson & Buckley, 2001). The duration of the power absorption phases was closer to those presented by Belli et al. (2002) and Johnson and Buckley (2001) than Bezodis et al. (2008). A possible explanation for the difference in agreement with previous studies could be the fact that the velocities of the athletes tested in this study were more similar to those tested by Belli et al. (2002) and Johnson and Buckley (2001), with the athletes tested by Bezodis et al. (2008) achieving higher sprint velocities. Another possible explanation for the difference could be the coaching that the athletes from different studies had received. The intra-athlete consistency of the power profiles agreed with the findings of previous studies of joint power, with the greatest consistency being at the ankle joint (Bezodis et al., 2008; Winter, 1980).

Knee

The power profiles for the knee joint were the least consistent across all athletes. The number of power phases at the knee joint during stance ranged from three (e.g. Athlete 3 left) to eight (e.g. Athlete 2 right). Mean power curves for all athletes started with an extensor power generation phase, followed by large power absorption and then generation phases. Some athletes then displayed further power absorption and generation phases, which were generally of smaller duration and magnitude than the previous phases. The magnitude of the power generated at the knee joint was also the least of the three joints; this agreed with the findings
of Bezodis et al. (2008) but contradicted the results of Belli et al. (2002) who found similar power magnitudes at the knee as the ankle joint.

**Hip**

The power profiles of the hip joint were the least consistent between trials. Most athletes displayed a large extensor power generation phase lasting for approximately 70\% of stance followed by a shorter power absorption phase. Some athletes displayed a short power absorption phase at the start of stance and a short power generation phase was also displayed by some athletes at the end of stance. The hip joint was the largest power generator for all athletes, with the exception of the right side for Athlete 9 where the hip joint was a net power dissipater. The finding that the hip joint was the greatest power generator for most athletes is in agreement with the findings of previous studies (e.g. Belli et al., 2002; Johnson & Buckley, 2001), with the general consensus being that the roles of the ankle and knee joints were to transfer the power generated at the hip to the track surface.

5.5.2 Kinetic Asymmetry Score

The KAS that was developed for this analysis benefited from being multifactorial and comprising a number of individual measures of asymmetry. The inclusion of numerous key measures of kinetic asymmetry for each athlete meant that the KAS assigned to each athlete considered both discrete data, relating to key instants during stance, and waveform data highlighting the development of the analysed kinetics throughout the entire stance phase. The multifactorial nature of the KAS meant that it was possible for athletes to have similar overall asymmetry scores caused by asymmetry of different kinetic variables. Conversely, athletes could have similar levels of asymmetry for some kinetic variables but have different overall asymmetry scores due to a large asymmetry present in one or more other variables. An example of two athletes having similar overall asymmetry scores comprised from different factors can be seen when considering Athletes 5 and 6. The asymmetry scores of the two athletes were very similar (6.96 and 6.25, respectively). However, the greatest contributor to Athlete 5’s asymmetry score was the asymmetry in joint power magnitude, whereas for Athlete 6 the greatest contributor was the phase difference at the knee joint. The possibility for athletes to achieve similarly large KAS values either by scoring highly for just one variable
or by accumulating a number of moderate scores is a benefit of the KAS as it considers the interaction of multiple key mechanical variables in the calculation of the score. If the KAS was calculated based on a small number of variables, it would be possible for kinetic asymmetry that developed over a number of variables to be overlooked; an example of this can be seen in the KAS for Athlete 4, which included significant asymmetry scores for seven different variables.

ABSθSYM scores reached much greater values for the kinetic asymmetry analysis than the kinematic analysis, with some scores approaching the maximum attainable value of 100%. One reason for larger ABSθSYM values was the greater occurrence of results that had different polarity for left and right sides or had one value that was close to zero. Due to the method of calculation of ABSθSYM, as one value approaches zero the ABSθSYM value approaches 50 (e.g. Athlete 4, WKNET). If a variable was dispersed around zero, such as WA_NET, it was possible for values to be almost completely asymmetrical (i.e. identical magnitude with opposite polarity), such as WA_NET for Athlete 9. The occurrence of values that approached zero highlights the benefit of using the ABSθSYM over other measures of asymmetry, such as the symmetry index (Zifchock et al., 2008b). As mentioned in Chapter 2, the symmetry index can lead to large falsely inflated results when the value for one side approaches zero. When using the ABSθSYM, there is a limit of 50% for values that display the same polarity and a limit of 100% for values of opposing polarity.

There was a large amount of intra-athlete variability present in many kinetic variables, which led to few variables being included in the asymmetry scores based on them displaying a significant difference between sides. The omission of variables from the asymmetry score based on significance was necessary so that false asymmetry was not reported due to extreme values from one trial. For asymmetry to be meaningful the difference between left and right limbs had to be greater than the intra-limb difference between trials, this ensured the robustness of the asymmetry score.

Joint asymmetry scores were calculated in favour of overall asymmetry of the lower limb, based on the findings of Vagenas and Hoshizaki (1991), who reported that asymmetry should be viewed as joint-specific. The argument for joint-specific
analyses of asymmetry is supported by the findings of this study; for example Athlete 4 showed 0% phase difference for the ankle, whereas the phase difference of their hip was 16% (Table 5.6).

Previous analyses of asymmetry have reported asymmetry of numerous kinetic variables (e.g. Burkett et al., 2003; Vagenas & Hoshizaki, 1991; Zifchock et al., 2006), but to the author’s knowledge, combining multiple factors to assign an overall score of kinetic asymmetry has not previously been performed. The advantage to calculating a general asymmetry score for each athlete is that the interaction of the overall asymmetry can be considered. An example of such analysis included in this research is the comparison between kinematic and kinetic asymmetry for each athlete, which would not be possible without both factors being quantified.

5.5.3 Implications of Kinetic Asymmetry

*Individual analysis*

Due to the large differences between individuals when analysing sprint running and the potential for misleading results when grouping results from different athletes (Dufek et al., 1995), this section of the results will first be discussed on an individual athlete basis. As kinematic data were analysed in the previous chapter for all athletes involved in this study, direct comparisons are presented between kinematic and kinetic asymmetry.

*Athlete 1*

The relatively large amount of kinetic asymmetry shown for Athlete 1 is unlike the kinematic asymmetry measured for this athlete, which was fairly central in the range of KAS values for the group. The most asymmetrical kinematic variable for Athlete 1 was knee flexion angle. However, net work performed at the knee joint was similar for both limbs of Athlete 1, as were minimum and maximum power values, offering no explanation for the kinematic asymmetry at the knee joint. The largest kinetic asymmetry of the knee joint was in the phase difference of the power curves, with a phase lag of 8% for the left knee compared to the right. The large asymmetry value reported for the power profiles of the ankle joint (65%) is a reflection of the consistency that was displayed for both left and right joints.
between trials, as the low standard deviations led to a large amount of the curves displaying a significant difference.

**Athlete 2**

There was a large difference in the KAS of Athletes 1 and 2 (19.35 and 28.67, respectively), despite them having similar KMAS (10.53 and 10.73). The most asymmetrical kinematic variable for Athlete 2 was \( y_{TD} \); however, there was no significant difference between the horizontal impulse of the left and right legs. The power profile comparisons found the ankle joint to have the least asymmetry, with 19% of the curve displaying a significant difference. The percentage of the power curve that was significant was greatest for the knee joint (69%) with the hip joint value (50%) lying in between the other two joints. Both event and profile asymmetry was observed at the knee joint for Athlete 2; however, there was no kinematic asymmetry observed in the knee flexion angle for the athlete.

**Athlete 3**

Athlete 3 had the third largest KAS, having had the second smallest KMAS. The largest contributor to the KMAS for Athlete 3 was \( y_{TD} \). The asymmetry reported for \( y_{TD} \) was reflected in the significant asymmetry for horizontal impulse, supporting the previously reported relationship between the two variables. The large asymmetry score observed for peak negative knee power was due to the minimum right power value being approximately three times larger than that of the left.

**Athlete 4**

Athlete 4 demonstrated the largest KMAS (27.60); however the KAS for this athlete was the fourth lowest (7.36) of the group. \( y_{TD} \) was very influential on the KMAS for Athlete 4; however, this was not paired with a significant difference in net horizontal impulse. An alternative outcome of the \( y_{TD} \) asymmetry is the significantly larger CT displayed for the left side, which was the side that demonstrated the larger \( y_{TD} \). 0% of the hip joint power profiles were found to be significantly different; this was caused by similarity in the profiles towards the start of stance followed by large intra-limb variability later in stance when the mean profiles diverged.
**Athlete 5**
The KAS calculated for Athlete 5 (6.96) was the third lowest of the group; this was not consistent with the KMAS (11.07), which was the second largest of the group. Maximum hip extension angle showed significant asymmetry in the kinematic analysis performed within Chapter 4. Kinetic event asymmetry for the hip joint was not significant. However, the hip joint did display asymmetry towards the end of the power profile presented in Figure 5.15. Athlete 5 was the only athlete to demonstrate a significant difference in mean support moment during stance, the results of which is reflected in the significant difference observed in minimum hip height for this athlete in Chapter 4.

**Athlete 6**
Athlete 6 displayed the lowest KAS (6.25), having scored fifth out of the eight athletes for the KMAS (9.86). Kinetic asymmetry was low for most factors. Interestingly, however, the power profile phase difference for the knee joint (20%) was the largest value of all joints for all athletes. The ankle profile showed the largest difference of the three joints with 14% of the profile being significantly different; this finding was linked to the only significant event score for Athlete 6, which was for net ankle work. 0% of the hip power profiles were significantly different; this finding is reflected in the similar shape of the profiles seen in Figure 5.15.

**Athlete 9**
Athlete 9's KAS was the second smallest (6.93) of the group. For Athlete 9 there was consistency between kinetic and kinematic asymmetry scores, as the KMAS for this athlete (4.52) was the smallest of the group. The agreement between KAS and KMAS for Athlete 9 was different to previous athletes and suggests that the interaction between kinematic and kinetic asymmetry may vary on an inter-athlete basis. The low kinetic asymmetry score for Athlete 9 was due to low scores for all profile measures, with no significant differences found between peak power values and less than 10% of power curves for each joint being significantly different between sides. The only large $ABS\theta_{SYM}$ score for Athlete 9 was for net ankle work (41.25), which was caused by the mean right value (0.04) being close to zero compared with that of the left side (0.32). There was a notable difference in the
consistency of the power profiles for the hip joint; with the standard deviation around the profile being much less for the left side than the right (Fig. 5.15).

**Athlete 10**
The kinematic asymmetry for Athlete 10 was essentially caused by asymmetry in the knee lift, hip extension angle and $y_{TD}$. Net hip work was significantly different between left and right sides, which could explain the asymmetry in knee lift and hip extension angle. This theory is reinforced by the large differences in hip power towards the end of stance (Fig. 5.15), which also led to a large amount of asymmetry in the peak power values for the hip.

**Group observations**
Relating the KAS to the KMAS for each athlete reported in Chapter 4, athletes varied as to their rank order based on kinematic and kinetic asymmetry (Fig. 5.16). Athlete 2 displayed a large KAS and a relatively large KMAS, whereas Athlete 4 showed a large amount of kinematic asymmetry but a smaller amount of kinetic asymmetry. A possible explanation for the inconsistency between scores is that, the kinetic mechanisms that cause the observed kinematic outcomes were used as a means of controlling for strength or technique imbalances in some athletes. Therefore kinetic asymmetry may have led to reduced kinematic asymmetry for some athletes. An observation that supports this theory is in the net work of the ankle, knee and hip joints, which was never significantly different between sides for more than one of the three joints. The reason that two joints did not show a significant difference for net work could be due to the asymmetry of one joint being a compensatory mechanism to overcome a technique imbalance. Therefore, the other joints may exhibit less asymmetry so that the correction provided by one joint is not negated by asymmetry of another joint further along the chain. It was noted that phase differences in power profiles tended to be opposite in direction at different joints for the same athlete; for example, Athlete 2 displayed a lag in the right hip joint profile but an opposite lag in the left knee joint profile.

Some athletes demonstrated a relationship between kinetic asymmetry of some variables and asymmetry of associated kinematic variables. An example of this was the link between asymmetry of $y_{TD}$ and horizontal impulse, which reinforced the relationship between $y_{TD}$ and braking force discussed in previous research.
(Kunz & Kaufmann, 1981; Mann & Herman, 1985). However, this relationship was not present for all athletes (e.g. Athlete 2). The lack of a relationship between kinetic and kinematic asymmetry for some athletes could endorse the use of kinetic asymmetry as a compensatory mechanism, used to reduce kinematic asymmetry. A similar compensatory mechanism was reported by Beyaert et al. (2008), when assessing knee kinetics of the intact limb in unilateral below-knee amputees.

The kinetic asymmetry of the support moment noted in this study (Appendix A.5) was of similar magnitude to that reported by Sanderson and Martin (1996) when comparing the kinetics of unilateral below-knee amputees. $\text{ABS}θ_{\text{SYM}}$ values for this variable ranged from 2.68% for Athlete 4 to 7.47% for Athlete 10, compared with values reported by Sanderson and Martin (1996) that relate to an $\text{ABS}θ_{\text{SYM}}$ value of 6.58%. The similarity of asymmetry results was not expected, due to the physical difference of the athletes tested, but may indicate that the magnitude of kinetic asymmetry for some variables is similar for able-bodied and amputee athletes.

5.5.4 Data Collection Considerations

For some kinetic variables intra-athlete variability was as large as the bilateral asymmetry, resulting in non-significant differences. The large intra-limb variability indicates that data collected from one limb may be representative of the data collected from the contralateral limb, although there could be a large amount of variability in the data. Some variables (e.g. ankle power) displayed much less variability and also displayed bilateral asymmetry for some athletes (e.g. Athlete 1) and for these variables reporting of data from one side of the body could be misleading. An example of the potential risk of analysing unilateral data can be seen when comparing the net horizontal impulse data for Athletes 1 and 6. If data were collected unilaterally from Athlete 6, it would be similar to data collected from the contralateral limb, with the difference between limbs being only 0.07 N·s. However, if the same data collection method was employed to collect data from Athlete 1, a difference of 6.40 N·s would be overlooked when reporting data from one limb. Another example advocating the collection of data from both limbs can be seen at the end of the hip power profile reported for Athlete 10, where there was difference in the magnitude, polarity and shape of the profiles of each limb.
5.6 Conclusion

In the introduction of this chapter, four key questions were identified and are addressed as follows:

1. *How can the level of kinetic asymmetry during sprint running be quantified for different athletes, considering multiple kinetic factors influential to sprint running?*

   The KAS was developed as a method for quantifying kinetic asymmetry during sprint running. The score was multifactorial, considering both event data and profiles of joint power. Collective variables combining ankle, knee and hip joints of the leg (e.g. support moment) were combined with joint specific variables (e.g. joint power) to enhance understanding of kinetic asymmetry mechanisms. Robustness of the KAS was ensured by including criteria for inclusion based on statistical significance. The development of the KAS has facilitated the quantification of overall kinetic asymmetry for each athlete, which in turn has enabled a comparison between kinematic and kinetic asymmetry.

2. *How asymmetrical are lower-limb kinetics of sprint running?*

   Overall kinetic asymmetry varied on an inter-athlete basis. Athlete 2 displayed the largest KAS, whilst the lowest score was calculated for Athlete 6. The large KAS score for Athlete 2 was the result of large asymmetry relative to the other athletes in many of the contributing factors. Some variables displayed consistently low asymmetry across the group of athletes (e.g. CT), whereas the asymmetry reported for other variables was inconsistent (e.g. net hip work). ABS0SYM scores for some variables were much larger than those calculated for step characteristics in Chapter 3 and kinematic variables in Chapter 4, with some values approaching the maximum achievable value of 100%.

3. *How is kinetic asymmetry related to kinematic asymmetry during sprint running?*

   Some athletes displayed a cause-and-effect relationship between kinematic and kinetic asymmetry for associated variables (e.g. yTD and horizontal impulse). However, other athletes seemed to demonstrate kinetic
asymmetry at joints where the kinematic outcome displayed a small amount of asymmetry. Comparison of kinematic and kinetic asymmetry scores further indicated the individual nature of sprint running, as no clear link was seen between the two scores (Fig. 5.14). Inconsistencies between kinetic and kinematic asymmetry for some joints could be due to compensatory mechanisms acting at some joints, as discussed by previous authors (Bezodis et al., 2008; Sanderson & Martin, 1996).

4. Based on the level of kinetic asymmetry present, is it appropriate to collect unilateral kinetic data on sprint running?

Based on the varied findings of this study, there were different implications for the collection of different kinetic data. For some variables (e.g. IMP, CT) there was a large amount of consistency between sides for all athletes, which indicates that it would be acceptable to collect data from one limb for these variables. However, some kinetic variables (e.g. joint power) displayed clear asymmetries for some athletes and collection of data from just one side could be misleading and possibly mask important characteristics relating to the athletes sprint running technique. It is recommended that, where possible, kinetic data are collected from both sides of the body. When this is not possible due to the logistical demands of collecting force data, data from one limb should be analysed with consideration of the possible asymmetry that may be present. Furthermore, due to the lack of a relationship between kinematic and kinetic asymmetry, it is not recommended that kinetic data collection considerations relating to asymmetry are made based on kinematic analysis.

This study has identified the kinetic asymmetry present in sprint running for a group of athletes ranging in ability. Part of the work discussed in this study has sought to offer a mechanical explanation for the kinematic asymmetry reported in Chapter 4. There was inconsistency found between athletes in the relationship between kinematic and kinetic asymmetry. Further inconsistency was reported in the variables that displayed kinetic asymmetry for each athlete. The following chapter will address the asymmetries found in Chapters 3 to 5 and consider how the asymmetry of step characteristics, kinematics and kinetics are linked.
CHAPTER 6 – GENERAL DISCUSSION

6.1 Introduction

The overall aim of this research was to investigate the phenomenon of lower-limb asymmetry in sprint running with the purpose of informing future sprint running research. The analysis of asymmetry has proved to be useful from performance (Vagenas & Hoshizaki, 1991), injury (Jacobs et al., 2005) and sports technology (Buckley, 2000) perspectives. However, very little information is available relating to asymmetry during sprint running. To meet the overall aim, four specific study aims were presented in Chapter 1, which were:

1) To gain an understanding of the asymmetry of step characteristics and associated kinematic variables for a range of sprint trained athletes.
2) To determine the underlying kinetic causes of the asymmetry observed in step characteristics and lower-limb kinematics on an individual athlete basis.
3) To develop a method of quantifying overall kinematic and kinetic asymmetry for individual athletes.
4) To quantify the influence of unilateral methods of data collection on biomechanical analyses of sprint running.

Chapter 2 provided a critical review of previous research into factors influencing successful sprint running and asymmetry in running and walking gait. Three chapters (3 to 5) successfully addressed research questions relating to the thesis aims. The development of specific aims within each chapter was an iterative process, where the aims of each study were formulated based on the overall thesis aims and the results of the preceding studies. Chapters 3, 4 and 5 addressed questions relating to the asymmetry present in step characteristics, the kinematic determinants of the step characteristics and the kinetic mechanisms that control the kinematic responses, respectively. In this chapter, the research questions outlined in Chapter 1 are discussed, linking the asymmetry observed in the studies contained in Chapters 3 to 5 to one another. The methods utilised in this research are reviewed and future directions for related research are discussed.
6.2 Addressing Research Aims

Chapter 3

There were two aims to Chapter 3; the first related to methodological development to enhance the collection of kinematic data. Therefore, the first aim of Chapter 3 was:

To develop methods for the collection of kinematic sprint running data that can be used during specific data collection sessions and, non-invasively, during athlete’s training or competition.

The CODA motion analysis system can be used to collect spatio-temporal data of active markers powered by small batteries (approximately 0.01 x 0.02 x 0.03 m) which are small in mass (approximately 0.022 kg). Advantages of collecting data using the CODA system include high accuracy, the automatic identification of markers and the nonexistence of ‘ghost’ markers, which can be caused by reflections when using passive motion analysis systems and the flexibility of the system’s layout. The accuracy of the CODA system was quantified in a biomechanics testing environment, during movements representative of those that occur during sprint running. Measures of distance were compared between markers attached to static and rotating rigid objects. Angular measures were also taken and compared to known values of similar magnitudes to those reported in sprint running (Mann & Herman, 1985), ranging from 37 to 158°.

Mean results demonstrated that the CODA system’s measurements of the distance between two markers, separated by ~1.30 m, varied by less than 0.001±0.002 m during moving trials. Angular measures were all within 1° of the known calculated values with standard deviation of less than 1°. Richards (1999) reported mean error of 0.276° for angles calculated using the CODA system, which were similar to the results seen in this study; however, the RMS error was less in this study (<1°) than that of 3.392° reported by Richards (1999). Based on the accuracy results, the CODA system was accepted as the ‘gold standard’ with which to compare other methods of data collection. Due to the high accuracy of the CODA system, it was advocated as the favourable method with which to collect positional data of athletes’ movements during sprint running. However, due to the need to attach markers to athletes and place scanners around the data
capture volume, there are instances when the use of automated motion analysis systems (including CODA) may not be possible. The unsuitability of automated motion analysis systems for the collection of data during competition and some training situations meant that another less-intrusive method was sought for such circumstances.

Following the quantification of the accuracy of the CODA system, a comparison was made between positional measurements of an athlete taken using the CODA system and reconstructed digitised video images using direct linear transformation (DLT). An advantage of many video-based methods is that they are non-intrusive and therefore allow data to be collected from training and competition situations when it may not be possible to attach markers to an athlete. Data were collected from one athlete performing maximal velocity sprint runs using both the CODA automated motion analysis system and video cameras. Digitised video images were reconstructed via 2D-DLT and 3D-DLT (Abdel-Aziz & Karara, 1971; Walton, 1981) in order to derive spatio-temporal data. Differences exist in the data collection requirements when collecting video data for reconstruction via 2D-DLT and 3D-DLT. Performing 3D-DLT provides additional information about depth that cannot be calculated when utilising 2D-DLT; however, 3D-DLT requires additional cameras and calibration points during data collection, which in turn leads to greater time demands associated with data processing. Many of the movements associated with straight line sprint running have been analysed in a single plane as a consequence of constraints on lateral motion and the need to stay within one lane (Johnson & Buckley, 2001). Antero-posterior motion has also been associated with successful performance more than medio-lateral movements (Hunter et al., 2004a).

The error calculated for the analysis of SL using 2D-DLT reconstructed in the track plane was 0.010 m over a field of view of approximately 6.00 m. The SL error was approximately twice the magnitude of that reported by Brewin and Kerwin (2003) using 2D-DLT (~0.005 m) for a similar field of view. However, the error reported in their study was for the calculation of individual locations, whereas SL involves the calculation of the displacement between two locations. Therefore, SL calculation is likely to contain more error than the calculation of one location.
Due to the reduced time demands and interference on the performance environment associated with 2D-DLT along with the ability to measure SL to within 0.010 m, this method was advocated as the most suitable for the calculation of step characteristics when it is not possible to place markers on an athlete. Angular results were less favourable for 2D-DLT compared with 3D-DLT, with mean RMSD for ankle, knee and hip joints ranging between 4.08 and 5.56°. For situations where joint angles are of interest and the use of CODA is not possible due to the requirement of placing markers on athlete, 3D-DLT was recommended which displayed a smaller mean error than 2D-DLT for ankle (3.96°), knee (4.23°) and hip (4.36°) joints.

The inter-step change in mass centre (CM) location is often used to quantify step velocity (SV) during sprint running. Forsell and Halvorsen (2009) highlighted the advantages of calculating CM position using minimal numbers of markers, including a reduction in the number of rejected trials and increased ecological validity. The calculation of horizontal sprint velocity was compared for CM locations calculated using unilateral and bilateral markers attached to an athlete and for the mid-point of bilateral markers located on iliac crests. Comparisons of CM velocity using all markers and those located on the left or right side of the body showed that there was a mean difference in stride velocity of 0.01 m∙s⁻¹. There were sections of the stride where markers located on one side of the body over and underestimated CM velocity calculated from markers located on both sides. The over and underestimation relative to full body CM velocity coincided with the contact of each foot. Velocity calculated for one side of the body underestimated full body CM velocity following TD of the foot of that side and then overestimated full body CM velocity during the swing and flight phase.

SV calculated using the mid-point of markers located on the iliac crests was also compared to CM velocity calculated using segmental weightings proposed by de Leva (1996) for all segments except for the foot, where those presented by Dempster (1955) were used with the addition of the typical mass of a running shoe (0.20 kg), as recommended by Hunter et al. (2004a). Velocity results showed that there was agreement between CM and mid-iliac velocity over a step cycle. Using two markers located around the pelvis to calculate velocity has the benefit of discounting the movements of the upper body, which is desirable when analyses
are focussed on the lower limbs. An additional advantage of the mid-iliac method was the fewer number of markers required to be attached to the athlete. Attaching a fewer number of markers to athletes increased ecological validity by minimising interference to the athletes, which can occur when wearing the large number of markers required to calculate full body CM position (Forsell & Halvorsen, 2009).

Horizontal velocity can be calculated using markers located on one side of the body in situations where bilateral data collection is not possible. However, when unilateral markers are used, calculation of velocity over less than a complete stride may lead to an over or underestimation due to the asymmetrical actions of an athlete’s limbs throughout a stride. Horizontal velocity derived using the mid-iliac method was similar to CM velocity over a step cycle, indicating that when an automated motion analysis system is used, SV can be calculated using two markers located on the iliac crests. The use of the mid-iliac method reduces the number of markers required to calculate SV in sprint running, increasing ecological validity due to the perceived negative effects of some athletes when wearing a large number of markers and reducing the number of rejected trials caused by marker displacement (Forsell & Halvorsen, 2009).

Suitable methods were developed in the first study of Chapter 3 to address the aim of the chapter’s second study, which focussed on asymmetry of step characteristics. The second aim of Chapter 3 was:

**To assess the amount of asymmetry present in step characteristics of two highly trained sprint runners.**

Step characteristics have been included in many previous analyses of sprint running in order to explain changes in velocity; this is largely due to the direct influence of step length (SL) and step frequency (SF) on the performance measure, SV, and also the negative interaction that exists between SL and SF. Hay (1994) and Hunter et al. (2004a) presented hierarchical models outlining the influence of kinematic and kinetic variables on SL and SF; however, the asymmetry of step characteristics has received very little attention. Therefore, the initial analysis of asymmetry in sprint running contained in this thesis focussed on step characteristics to determine the extent of asymmetry present in the highest order variables influencing success.
Step characteristics were calculated for two well-trained sprint athletes during maximal velocity sprint training sessions. The symmetry angle ($\theta_{\text{SYM}}$) score of asymmetry, proposed by Zifchock et al. (2008b), was utilised to quantify the asymmetry present within the athletes’ step characteristics. Both athletes demonstrated a small amount of asymmetry in all three step characteristics, with $\theta_{\text{SYM}}$ values being <1% for both athletes, with 0% representing no asymmetry being present. The small amount of asymmetry observed in SV was hypothesised, in Section 3.2.1, to be due to the requirement of athletes to stay within their running lane during a sprint race. Asymmetry was largest for SF for both athletes, with similar amounts of asymmetry for SV and SL.

Both athletes displayed a similar amount of asymmetry for SV values ($\theta_{\text{SYM}}$ values of 0.40% and 0.37% for Athletes A and B, respectively), despite differences in the performance levels of the two athletes (mean SV values of 10.34±0.20 and 9.34±0.14 m·s$^{-1}$ for Athletes A and B, respectively). For both athletes the SV asymmetry was caused by a larger asymmetry in SF (0.83% and 0.73%), the effect of which was reduced by a SL asymmetry smaller in magnitude and opposite in direction to SF (-0.45% and -0.36%). The direction of asymmetry was represented by the polarity of the $\theta_{\text{SYM}}$ score (i.e. the positive $\theta_{\text{SYM}}$ for SF shown by both athletes mean that the left-to-right (L-R) SF value was larger than the right-to-left (R-L) step, whereas the negative $\theta_{\text{SYM}}$ for SL meant that the R-L SL value was larger than the L-R value). The opposite direction of asymmetry in SL and SF reinforced the inverse relationship that has previously been suggested to exist between the two factors (Hunter et al., 2004a; Kunz & Kaufmann, 1981). It was evident that as one factor increased for one side of the body, the other factor experienced a decrease due to the conflicting demands of the two factors.

Comparing SF and SL with SV for both athletes, changes in SV appeared to be caused by changes in SF more than SL. It was hypothesised in Section 3.2.1 that the step characteristic that was more closely linked to SV would have a larger influence on SV asymmetry. Both athletes analysed in the study appeared to be SF dominant in relation to SV performance and both athletes also displayed a larger $\theta_{\text{SYM}}$ score for SF than SL, indicating that the dominant step characteristic had a greater influence on SV asymmetry.
A limitation identified with the existing $\theta_{SYM}$ was the fact that intra-limb variability was not considered in the asymmetry calculation. To establish the effect of this, a $t$-test was employed to determine the significance of inter-limb step characteristic differences, relative to intra-limb variability. The results of the $t$-test identified that, whilst $\theta_{SYM}$ values were similar for both athletes, asymmetry was only significant for Athlete A. This finding highlighted the need to consider intra-limb variability when calculating asymmetry.

**Chapter 4**

Following the significant differences observed between left and right steps for Athlete A in Chapter 3, Chapter 4 focussed on asymmetry of kinematic variables that have been linked to success during sprint running. The asymmetry in step characteristics reported in Chapter 3, indicated a close relationship between the asymmetry present in the step characteristic variables. However, to gain understanding of the underlying causes of the step characteristic results, a kinematic analysis was required (Hunter et al., 2004a). The main aim of Chapter 4 was:

**To investigate asymmetry of the kinematics of the lower limbs during sprint running.**

Having discovered significant asymmetries in step characteristics of a highly trained athlete, further analysis was required to determine the extent of asymmetry present in the kinematic variables that control step characteristics. The complex interaction of sprint kinematics could potentially allow larger asymmetries to be present in some variables, the effects of which are negated by asymmetry present in another variable. An understanding of kinematic asymmetry is important from a biomechanical data collection perspective to determine whether data must be collected bilaterally or whether symmetry can be assumed, allowing data to be collected from just one side of the body (Karamanidis et al., 2003). Submaximal running asymmetry has been investigated from an injury perspective with asymmetry being suggested as a contributor to injury predisposition in one side (Zifchock et al., 2006); however, this form of analysis has not yet been extended to include sprint running.
Chapter 4 involved quantifying kinematic asymmetry for 10 athletes of varying sprint running ability, with mean SV values ranging from 8.54 to 10.20 m·s\(^{-1}\). Data collection occurred during dedicated sessions rather than during athlete’s own training sessions, allowing markers to be placed on the athletes during data collection; therefore, the CODA system was utilised for the collection of spatio-temporal data.

Kinematic asymmetry was quantified for each athlete using the interaction of eight variables that have been associated with successful sprint running performance from either biomechanical (Hay, 1994; Hunter et al., 2004b; Mann, 1985) or coaching (Thompson et al., 2009) perspectives. A composite kinematic asymmetry score (KMAS) was calculated for each athlete as well as the more detailed measures of kinematic asymmetry. The KMAS was calculated based on \(\theta_{SYM}\) scores of each variable. A novel feature of the KMAS was the consideration of intra-limb variability; this was achieved by excluding \(\theta_{SYM}\) scores for variables that displayed larger intra-limb variability than the difference observed between limbs.

It was important to quantify kinematic asymmetry using a number of kinematic variables associated with success to provide a comprehensive analysis of kinematic asymmetry. Inclusion of fewer variables could have resulted in misleading conclusions being drawn about the magnitude of asymmetry because of the differences in asymmetry present in different variables highlighted in Chapter 3 for step characteristics. For example, if just SF asymmetry had been quantified in Chapter 3, important information about the smaller magnitude and opposite direction of asymmetry present in SL would not have been reported. Inclusion of the KMAS along with detailed kinematic measures of asymmetry allowed the specific causes of the KMAS to be identified for each athlete as well as an overall score of kinematic asymmetry.

Each athlete’s KMAS was calculated using four different methods, all of which involved the addition of \(\theta_{SYM}\) scores for each kinematic variable, with some methods excluding \(\theta_{SYM}\) scores for variables that did not display statistical significance. The method of calculating KMAS that was selected as the most appropriate involved multiplying the \(\theta_{SYM}\) score for each variable by either 0, 1 or 2 depending on the results of a t-test and ANOVA, with 0 indicating that neither tests were significant, 1 meaning that one of the two tests displayed significance and 2
indicating that both tests showed a significant difference. The t-test was used to determine the significance of the difference between left and right values for each variable, whilst the ANOVA was used to test the significance of each variable’s $\theta_{SYM}$ compared to that of SV so that kinematic asymmetries caused by changes in running velocity did not influence the KMAS for that athlete. The benefit of calculating an overall asymmetry score for each athlete was that it allowed kinematic asymmetry to be quantified and compared for a range of athletes. The calculation of the KMAS and inclusion of tests for significance also allowed the variables that influenced each athlete’s KMAS to be easily identified, which facilitated the comparison of which kinematic variables had the greatest effect on asymmetry for each athlete.

Inter-athlete asymmetry differences were present in the group of athletes tested. There did not appear to be any relationship between kinematic asymmetry and sprint performance. Athletes 3 and 7 displayed similar mean velocities (9.00 and 9.04 m·s$^{-1}$) but the kinematic asymmetry calculated for Athlete 3 (7.22) was less than half the magnitude of that calculated for Athlete 7 (15.43). The variables that displayed the most asymmetry were not consistent across all athletes, with the variables that displayed significant asymmetry, and hence contributed to the KMAS, being different for all athletes. However, the $\theta_{SYM}$ score for SV was low (<1%) for all athletes when compared to the other variables; this indicated that the asymmetry present in other kinematic variables was a compensatory response to either a strength imbalance (Vagenas & Hoshizaki, 1991) or asymmetry in another variable (Vagenas & Hoshizaki, 1992). The inter-athlete differences in overall KMAS and the variables that contributed to them reinforce the importance of individual analysis, discussed by Dufek et al. (1995). Since asymmetry in the performance measure (SV) was low for all athletes, the assumption could be made that the amount of asymmetry in other kinematic variables would be similar for all athletes; however, this was not the case and kinematic asymmetry varied on an inter-athlete basis.

The largest amount of asymmetry calculated for one variable was 6.68% for touchdown distance (y$_{TD}$) of Athlete 4. Step characteristic asymmetry was generally lower than the other kinematic variables, with all step characteristic $\theta_{SYM}$ values being less than 2.00%. The opposite direction of SL and SF asymmetry
reported in Chapter 3, whereby the step displaying a larger SL value exhibited the smaller SF value, was also found in the kinematic results of Chapter 4. The smaller asymmetry seen for step characteristics compared with the other kinematic variables indicated that the effect of larger asymmetries displayed by other variables may have been reduced by opposing asymmetry present in other variables, further supporting the suggestion of compensatory mechanisms made by Vagenas and Hoshizaki (1992). The variable that displayed a significant difference between sides for the most athletes (5) was minimum knee flexion angle. Possible causes of the large occurrence of asymmetry in minimum knee flexion angle compared with the other variables could have been knee strength imbalances, as reported by Vagenas and Hoshizaki (1991), or asymmetry in the range of motion at the joint (Warren, 1984). Conversely, minimum hip height during stance was significantly different between sides for the least number of athletes (2); Karamanidis et al. (2003) also reported very small amounts of asymmetry in minimum hip height during submaximal running. The small amounts of asymmetry present in minimum hip height may be necessary to prevent collapse of the contact limb whilst the athlete is in contact with the track; however, asymmetry may exist in the individual joints of the lower limbs and be compensated for by the other joints so that the overall effect is minimised, as suggested by the support moment theory of Winter (1980). To determine whether individual joint asymmetry and compensatory mechanisms existed a joint-specific analysis was required, which was performed in Chapter 5.

From a data collection perspective, the magnitude of kinematic asymmetry was found to be inconsistent between variables and between athletes. For this reason it was recommended that symmetry is not assumed when collecting kinematic data. For some variables and athletes it may not be a problem to collect unilateral data and assume the presence of symmetry but it appears that this is only the case for specific athlete-variable combinations. Based on the differences observed in the magnitude of asymmetry, the research presented suggests the need for a screening test prior to the collection of kinematic data to assess the kinematic asymmetry of the variables of interest. Ciacci et al. (2010) included a preliminary test of asymmetry in their study on braking and propulsive phases of sprint running. However, they did not include all athletes in the preliminary test and, therefore, could have overlooked asymmetry in the other athletes included in their
A screening test quantifying athletes’ kinematic asymmetry would allow an informed decision to be made on whether bilateral data are required, based on the influence that collecting data from just one side of the body would have on the results. An example of the potential lost information when employing a unilateral analysis was outlined in Chapter 4. For example, if $y_{TD}$ data were collected unilaterally from Athlete 4, the difference of 0.06 m observed between left and right legs would have been lost. Conversely, $y_{TD}$ was not different between sides for Athlete 10; however maximum knee lift results, which were not significantly different between sides for Athlete 4, displayed a significant difference of 0.04 m for Athlete 10. Many previous studies investigating kinematics of sprint running have not considered the phenomenon of asymmetry. The results presented in Chapter 4 highlight the potentially important information relating to asymmetry within athletes that could be overlooked when unilateral methods of data collection are employed. The influence of asymmetry on data collection has been investigated for submaximal running (Zifchock & Davis, 2008), but until now the effects of this on sprint running have not been quantified.

**Chapter 5**

Having found a large amount of kinematic asymmetry in some variables, such as $y_{TD}$ and minimum knee flexion angle, and a smaller amount of asymmetry in other variables, such as hip height, a study of individual joint kinetics was required. Winter (1980) suggested that compensatory mechanisms may exist in the ankle, knee and hip joints to control the overall support of the lower limbs during ground contact. An inverse dynamics analysis (IDA) was adopted to allow calculation of net joint power acting at the main joints of the lower limbs. Sadeghi *et al.* (2000) advocated joint power as a good measure with which to assess kinetic asymmetry due to the inclusion of the joint moment and angular velocity. Vagenas and Hoshizaki (1991) suggested that asymmetry should be analysed on an individual joint basis so that compensatory mechanisms present in any joints are not overlooked. The central aim of chapter 5 was:

**To investigate the kinetic asymmetry of the lower limbs during sprint running, in light of the kinematic asymmetry reported in Chapter 4.**

Ground reaction force and centre of pressure (COP) data were collected via force plates located under the running track surface to allow an IDA to be undertaken.
Johnson and Buckley (2001) highlighted the increased number of rejected trials when collecting ground reaction force (GRF) data, due to foot contacts occurring outside of the force plate boundaries. To increase the occurrence of foot contacts with the force plate and hence, reduce the number of rejected trials, two force plates were mounted end-to-end along the sagittal plane. Utilising two force plates doubled the area of GRF data collection compared to one force plate; however, the number of acceptable trials could be further increased if steps that overlapped the boundary between the two plates could be used. Therefore, a verification study was undertaken to assess the accuracy of GRF and COP location data when contact occurs on two force plates.

A fixed-axle rigid trolley was loaded so that the vertical GRF applied to the track was representative of that reported during sprint running. The trolley wheel was rolled across the boundary between the two plates to represent the motion of an athlete’s foot as the athlete ‘rolls’ over the top of it during the contact phase. Marker positional data and COP data collected from the trolley as it was rolled across the boundary between two force plates showed agreement in the horizontal movement of the trolley in the sagittal plane. The difference between the trolley position calculated using active CODA markers and COP was consistent throughout the transition from one plate to the other, with a mean difference of 0.002±0.003 m. Comparing results for different locations along the plate in the medio-lateral axis, the mean error was similar for left, middle and right locations although the standard deviation was lower for trials near the middle of the plate. It has been reported that the accuracy of piezoelectric force plates is greatest towards the centre of the plate and decreases when contact occurs outside of the measurement cells (Bobbert & Schamhardt, 1990), towards the extremities of the plate; this finding was reflected in the COP results of this study.

Positional differences that were observed between movement of the trolley calculated via COP location and the location of attached active markers were used to test the sensitivity of joint power values calculated using COP data. The mean (0.0027 m) and largest (0.0076 m) differences in COP resulted in ankle, knee and hip joint power RMSD values ranging from 0.27 to 1.47% and from 0.73 to 4.02%, respectively. The largest RMSD effect of COP error on joint power was observed for the knee joint, which was due to smaller power values occurring at this joint.
The effects of COP error on joint power at the ankle and hip joints were approximately a quarter of the magnitude reported for the knee joint. The effects of COP errors on joint powers were similar to those reported for other positional errors, such as digitising error (Bezodis et al., 2008).

Eight athletes participated in the kinetic study described in Chapter 5. All eight athletes had been participants in the kinematic study described in Chapter 4, which provided insight into their kinematic asymmetry. An IDA was utilised to calculate individual joint kinetic data, using the kinematic data from the trials analysed in Chapter 4. Kinetic asymmetry was quantified for each athlete as a combination of the asymmetry apparent in multiple kinetic variables that are influential to sprint running. Variables analysed were related to the kinematic determinants of success investigated in Chapter 4. Kinetic asymmetry score (KAS) contributors included discrete measures, such as net horizontal and vertical impulse, and values summarising the asymmetry calculated for continuous data, including joint power throughout stance. The kinetic analysis included variables that were the result of collective joint actions (e.g. support moment, GRF); whilst others were analysed on an individual joint basis (e.g. joint power). Combining collective measures with joint specific variables gave an indication of the asymmetry occurring at each joint, along with the net effect of all of these joint asymmetries. The inclusion of individual joint and net effect variables gave indication of compensatory mechanisms, as discussed by Winter (1980), and their effects on asymmetry.

**Development of kinetic asymmetry score**

Asymmetries of discrete variables were used to calculate a collective score by summing the \( \theta_{\text{SYM}} \) scores for each variable that displayed a significant difference between left and right values; the combined score was termed the ‘event asymmetry score’. Continuous joint power profiles were analysed to allow greater insight into the interactions of the ankle, knee and hip joints during stance, as recommended by Sadeghi et al. (2000). Continuous data were used to calculate a ‘profile asymmetry score’, which included \( \theta_{\text{SYM}} \) measures of magnitude, phase, time and overall difference for each joint. \( \theta_{\text{SYM}} \) scores were only included in the profile asymmetry score if the variable displayed a significant difference between left and right sides. The use of significant difference between left and right values
meant that for a variable to be considered to display asymmetry, and hence contribute to an athlete’s KAS, the difference between the left and right sides had to be greater than the variability present within one side. A global KAS was calculated for each athlete by adding the event and profile asymmetry scores. The KAS allowed comparison of overall kinetic asymmetry between athletes and also allowed comparison with the KMAS for each athlete.

**Kinetic asymmetry results**

Asymmetry values calculated for the kinetic variables included the largest values of all the studies, with the \( \theta_{\text{SYM}} \) calculated for net work at the ankle joint for Athlete 10 (93.23%) being close to the maximum attainable value of 100%. Large \( \theta_{\text{SYM}} \) values occurred in the kinetic analysis due to the inclusion of variables that were close to zero and could include both positive and negative values of similar magnitude, such as joint work performed at the ankle. The inclusion of values close to zero reinforced the use of \( \theta_{\text{SYM}} \) as a measure of asymmetry, due to the artificial inflation of asymmetry associated with other measures of asymmetry, such as the symmetry index (Herzog et al., 1989; Zifchock et al., 2008a). The number of variables that displayed a statistically significant difference between sides varied between athletes. Some athletes exhibited a large difference between the mean values calculated for each side; however the intra-side variability was very large relative to the inter-side differences, meaning that the difference between sides was not statistically significant. Therefore, these measures did not contribute to the calculation of the KAS. Both variables based on discrete and continuous data displayed asymmetry for some athletes. Athlete 2 had the largest KAS, due to asymmetry present in the majority of the possible contributing variables. Conversely, Athlete 6 displayed more asymmetry in continuous variables (e.g. joint power phase difference) than discrete variables, evident from the second lowest event asymmetry score of all athletes tested. The larger \( \theta_{\text{SYM}} \) scores seen for some kinetic variables than those reported for kinematic variables provided further indication that kinetic asymmetry of some variables may be used as a mechanism for reducing kinematic asymmetry and controlling the output variables.

Asymmetry present in some kinetic variables was associated with asymmetry in corresponding kinematic variables. An example of the link between kinematic and
kinetic asymmetry that was observed for some athletes was the significantly different $y_{TD}$ seen in Chapter 4 and horizontal impulse in Chapter 5. Similarly, the only athlete to display asymmetry in the mean support moment during stance (Athlete 5) also displayed significant asymmetry in minimum hip height during stance. The link between asymmetry of kinetic variables and related kinematic measures was not always apparent. For example, Athlete 4 displayed a significant asymmetry in $y_{TD}$, whilst no asymmetry was reported for the related kinetic measure of horizontal impulse. One explanation for the inconsistency seen between asymmetry of related kinetic and kinematic variables is the possible compensatory mechanisms acting at some joints, as discussed in previous studies (Bezodis et al., 2008; Sanderson & Martin, 1996). These compensatory mechanisms may be employed by the athlete to overcome strength or physical imbalances, as could be the case when kinetic asymmetry leads to an apparent reduction in kinematic asymmetry.

Comparison of KMAS and KAS indicated that there was no relationship between the two scores within athletes. Some athletes (e.g. 6 and 9) displayed similarly low scores for both KMAS and KAS in relation to the other athletes, whereas Athlete 2 displayed a large amount of kinetic asymmetry and a moderate KMAS in comparison to the other athletes. The lack of a relationship between kinetic and kinematic asymmetry reinforces the individual nature of sprint running as each athlete displayed an individual interaction between kinetic and kinematic asymmetry. It appears that kinetic asymmetry may be the cause of kinematic asymmetry in some variables for some athletes; whereas for other athletes, kinetic asymmetry may reduce kinematic asymmetry and may be a required compensatory mechanism due to strength or physical imbalances (Beyaert et al., 2008; Vagenas & Hoshizaki, 1992).

Due to the variation in the magnitude of asymmetry reported for different kinetic variables, it was recommended that kinetic data should be collected bilaterally where possible. Some variables (e.g. vertical impulse, CT) displayed a large amount of consistency between sides for all athletes, which indicates that it would be acceptable to collect data from one limb for these variables. However, other variables (e.g. joint power) showed a large amount of asymmetry for some athletes. For variables that display a large amount of asymmetry, collecting data
from one limb could lead to important information relating to different movements of the contralateral limb being overlooked.

The magnitude of kinetic asymmetry differed for the same variable between athletes. Two athletes (e.g. 6 and 9) showed no significant asymmetry for peak magnitude of joint power at the ankle, knee or hip; conversely, Athlete 2 displayed significant asymmetry at all three joints, ranging from 7.12% for the ankle to 17.92% for the knee. The difference in asymmetry between athletes indicated that if peak joint powers were of interest, a unilateral approach would be suitable for Athletes 6 and 9. However, if a unilateral approach was employed for Athlete 2 results would be drastically different depending on which limb data were collected from. Conversely, if data were pooled or averaged for both limbs, a large amount of intra-trial variability would be present and the results could be a ‘mythical average’ that is not representative of either limb (Dufek et al., 1995).

It was recommended from the kinematic asymmetry analysis in Chapter 4 that athletes are pre-tested for asymmetry if considering a unilateral method of data collection. Whilst this would be a beneficial consideration prior to the collection of kinetic data, it may not be logistically possible to collect the required data to perform such a pre-test. When information about an athlete’s kinetic asymmetry is not known and bilateral data collection is not possible, data from one limb should be analysed; however, the possibility of kinetic asymmetry should not be ignored. As no clear relationship was observed between kinetic and kinematic asymmetry, it is not recommended that kinetic data collection considerations relating to asymmetry are made based on kinematic analysis. This was exemplified by the results for Athlete 3, who had the second smallest KMAS but the third largest KAS.

6.3 Appraisal of Approach

The collection of spatio-temporal and force data within this research has necessitated the development of novel methods that can be used unobtrusively in training and competitive situations and the validation of more traditional methods for use in dedicated data collection scenarios. Data analysis has also required the development of new methods to allow asymmetry of specific kinematic and kinetic variables to be quantified, as well as providing a global asymmetry score for each
athlete to allow comparison with other athletes. Quantification of asymmetry has developed on the method advocated by Zifchock et al. (2008b), which allowed calculation of asymmetry between discrete data points without the limitations of other methods such as the symmetry index (Herzog et al., 1989).

Kinematic data collection
Methodological limitations existed that restricted the collection of kinematic data to small sections of each sprint run (approximately 8 m in the studies of this thesis) due to the field of view available with the positional requirements of the motion analysis scanners. As discussed in Chapter 3, the high accuracy and automated collection benefits of using the CODA system were much greater than with traditional video-based methods. However, the field of view when using the CODA system is limited by the number of scanners and positional restrictions of the scanners caused by the performance arena. Following pilot work to maximise the field of view for bilateral data collection, scanners were positioned in pairs separated by 4.00 m along the running lane with the cables connecting the scanners suspended above the running track so that the athlete could pass underneath them without the need to alter their step pattern.

Surface markers located on joint centres allow accurate calculation of segmental movements in the sagittal plane during running (Reinschmidt, van den Bogert, Murphy et al., 1997). A benefit of surface anatomical markers located on joint centres was that they remained attached to the athlete throughout sprint trials and were very rarely displaced by the athlete, which would have led to trials being rejected. When using surface anatomical markers for the collection of spatio-temporal data it was only possible to accurately calculate 2D joint angles in the sagittal plane. Therefore, both kinematic and kinetic analyses were limited to excluding lateral motion and internal segment rotation. Similar 2D analyses have been utilised in many previous studies of sprint running (Bezodis et al., 2008; Hunter et al., 2004b; Mann & Herman, 1985) due to the occurrence of the majority of movement in the sagittal plane and the restriction of the athlete’s lateral movements by the fact that they must stay within the lane lines. The collection of 2D kinematic data was also the result of difficulties associated with current methods used for the collection of 3D data. Recent technological advancements have allowed the collection of segment rotations and 3D positions through the use
of segmental clusters (Exell et al., 2009). However, the use of such clusters is limited in the analysis of sprint running due to the high velocities and large impacts involved, which can cause movement of the clusters relative to the underlying segment. This approach was experimented with early in the study but rejected in favour of the conventional surface marker approach to focus the attention on asymmetry rather than potential cluster movement and interference with athletes’ actions during sprint running. The use of segmental clusters would not have been suitable in this research due to the movement of clusters relative to the underlying segment causing trials to be rejected and leading to potential errors in the kinematic data.

Kinetic data collection
When performing a kinetic analysis using data collected from force plates, some trials have to be discarded due to foot contacts not occurring within the boundary of the force plates (Johnson & Buckley, 2001). From a data collection perspective, it is of interest to reduce the number of discarded trials so that athletes are not fatigued by having to perform additional sprint runs. Through utilising two force plates for the collection of GRF data, the number of useable trials was increased for the investigations undertaken. The increased data capture distance when using two force plates (1.80 m) instead of one force plate (0.90 m) led to a 2.5 times increase in the area of acceptable foot contacts compared to using one force plate, due to the inclusion of foot contacts that occurred on the boundary between the two force plates. The increased force data collection area allowed a larger number of trials to be collected for IDA than has been reported in many previous studies during maximal velocity sprint running. Larger trial numbers allowed a parametric statistical analysis to be employed, quantifying significance of observed differences.

6.4 Future Directions for Research
The research in this thesis has provided an innovative assessment of the asymmetry that is apparent in a range of trained athletes during maximal velocity sprint running. Methods were developed to maximise the number of trials that could be recorded with data collected from trained sprint runners covering a range of ability levels. The inclusion of more trials allowed parametric statistical methods
to be employed so that bilateral differences that were not significant were not included in the quantification of asymmetry. Athletes were not included in the studies that performed at an elite level, due to the lack of availability of such athletes. Future comparison of asymmetry between elite athletes and those performing at a sub-elite level would be beneficial from both coaching and data collection perspectives. However, elite athletes are less common, have limited time to contribute to research studies within their strict training regimes and are often concerned about potential injury. Video-based methods of data collection could be applied to training and competition, but analysis would be restricted to the reliable variables highlighted in Chapter 3.

The development of a method for force data collection using multiple force plates allowed a larger number of steps to be analysed than if one force plate had been used. However, it was only possible to collect force data from one foot contact from each sprint run. The inclusion of extra force plates and scanners in future studies would allow a larger portion of each run to be collected and could allow for consecutive steps to be analysed via an IDA; however, the substantial costs associated with such equipment often limits the number of force plates and scanners available. If it were possible to collect force data from multiple foot contacts per sprint run, the IDA of consecutive steps would give valuable insight into the step-to-step effects of kinetic asymmetry and whether asymmetry is caused by one side having to compensate for the movements of the other in the preceding step.

Whilst motion in the sagittal plane is dominant in sprint running, it would be useful from both a coaching and injury perspective to examine the asymmetry of movements that occur in the other planes (McClay & Manal, 1999). It is the experience of this author that, at current, the use of rigid clusters attached to athletes for the automated 3D tracking of body segments is limited to applications within studies of submaximal running. In maximal velocity sprint-running the movement of clusters relative to the underlying soft tissue can lead to the rejection of large numbers of trials and error introduced to the calculated variables. In addition, the reliability of segmental clusters located towards the middle of segments has not been established during maximal velocity sprint running.
Therefore, future investigations utilising cluster based methods of data collection should be wary of the effects of soft tissue motion on performance.

The studies contained within this thesis addressed the amount of asymmetry that occurred during maximal velocity sprint running. Sprint running is of global interest due to the small margins that can separate champions from their competitors and the immense esteem that is associated with holding the world record in the sprint events. Global focus on sprinting has been growing over the past few years due to the magnitude by which the 100 m world record has recently been broken. The maximum velocity phase of a sprint run is of particular public and scientific interest as it is when the athlete is working at their limits. The level of asymmetry present in other phases of a sprint run, such as the acceleration phases (Kugler & Janshen, 2010), or during bend running (Bezodis & Gittoes, 2008) could differ greatly. Furthermore, the start phase includes the athlete exiting the blocks which can be a very asymmetrical movement for some athletes in terms of the foot placement that they choose when arranging their starting blocks (Guissard et al., 1992). It would be useful to look at the evolution of asymmetry throughout a race to see how asymmetry changes throughout the different phases in relation to performance.

A contentious issue that has received much media attention in recent years is the eligibility of amputee athletes to run in able-bodied competition. The controversy surrounding this issue drew much recent public interest following the disqualification and subsequent reinstatement of an amputee sprint runner from international competition (Eason, 2008). The difference in opinion on whether artificial limbs offer a performance advantage has been the topic of recent debate (Weyand & Bundle, 2009). The inclusion of asymmetry in the analysis of artificial limb contributions to sprint running may offer greater insight into the differences that are present between athletes with and without artificial limbs. Analysis of asymmetry present in unilateral and bilateral amputee athletes could also further understanding of this topic. However, the collection of data from lower-limb amputee sprinters poses unique challenges due to the reduced musculature present at some of the joints. Asymmetry may also be useful in the development of prosthesis for unilateral amputee athletes, when a direct intra-subject comparison between an affected and intact limb are possible (Hillery & Wallace, 2000).
6.5 Final Note

The aims of this research were:

1) To gain an understanding of the asymmetry of step characteristics and associated kinematic variables for a range of sprint trained athletes.

2) To determine the underlying kinetic causes of the asymmetry observed in step characteristics and lower-limb kinematics on an individual athlete basis.

3) To develop a method of quantifying overall kinematic and kinetic asymmetry for individual athletes.

4) To quantify the influence of unilateral methods of data collection on biomechanical analyses of sprint running.

These aims have been achieved by addressing research questions relating to the asymmetry of step characteristics, kinematics and kinetics of the lower limbs. A kinematic analysis highlighted some of the areas where athletes displayed kinematic asymmetry. This was followed by a kinetic analysis, which identified potential compensatory mechanisms and causes of the kinematic asymmetries.

The methods developed within this thesis have enabled the quantification of asymmetry of discrete and profile data, which led to the creation of an innovative score of athlete’s global kinematic and kinetic asymmetry. Quantification of the asymmetry present in sprint running has been investigated from a data collection perspective, with the potential effects of unilateral data collection reported in each study. The development of the KMAS and KAS allowed comparison of asymmetry between athletes. This research has identified some important methodological considerations that should be made relating to the potential asymmetry that could be overlooked when analysing sprint running using a unilateral approach. Furthermore, from a coaching perspective, asymmetry has been evident in step characteristics, kinematics and kinetics of sprint running, which could influence future training of sprint runners by informing the coaching-biomechanics interface (Kerwin & Irwin, 2008). The work contained within this thesis has instigated the analysis of asymmetry in sprint running; further related research topics have been suggested so that understanding of asymmetry during sprint running can be further enhanced.
References


APPENDIX A – DATA

Appendix A contains additional information to supplement the results presented in Chapters 3 to 5.

Appendix A.1 Pages 206-7
Appendix A.2 Page 208
Appendix A.3 Page 209
Appendix A.4 Page 210
Appendix A.5 Page 211
Appendix A.6 Pages 212-4
APPENDIX A.1 – DIGITISER ACCURACY CHECK

Digitiser accuracy was checked by comparing digitised positions of markers located on the track surface with their measured locations. The location of calibration markers and markers used for the accuracy test are shown in Figure A.1.

Figure A.1. Location of calibration marks (grey) and known locations (black) used for calculation of digitiser accuracy.

Figure A.2 contains a graphical representation of the digitiser error for different locations on the track surface. The least error was found to be in the middle of the lane.

Figure A.2. Graphical representation of calibrated section of track surface showing mean digitiser error at each location. Error was smallest (dark blue) towards the middle of the calibrated area and largest (red) towards the middle of the outside edges.
Digitiser error results are presented in Table A.1, which shows the x and y components of the error. The largest error values were found to be in the medio-lateral (x) direction, which is not included in the calculation of SL.

Table A.1. Position of known locations used for validation of digitiser accuracy and error calculated at each location.

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<th>X (m)</th>
<th>Measured position</th>
<th>Error</th>
<th>Measured position</th>
<th>Error</th>
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<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>4.000</td>
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<td>0.000</td>
<td>0.005</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>4.000</td>
<td>0.006</td>
<td>0.234</td>
<td>-0.002</td>
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<td></td>
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<tr>
<td>15</td>
<td>4.000</td>
<td>0.007</td>
<td>0.936</td>
<td>-0.011</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>4.000</td>
<td>0.002</td>
<td>1.170</td>
<td>-0.002</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX A.2 – CLARIFICATION OF KINEMATIC VARIABLES ANALYSED

Figure A.3 shows the kinematic variables that were measured in Chapter 3. SV, SL and SF were all measured over one step cycle; $z_{H_{\text{MIN}}}$, $z_{K_{\text{MAX}}}$, $\theta_{K_{\text{MIN-FLEX}}}$ and $\theta_{H_{\text{MAX-EXT}}}$ were all calculated as the respective minimum and maximum values during stance and $y_{TD}$ was calculated as the value at the instant of touchdown.

Figure A.3. Graphical representation of the kinematic variables analysed in Chapter 4.
APPENDIX A.3 – INTER-SESSION VELOCITY CHECK

Table A.2 displays results of the comparison of step velocity for all athletes that were involved in two separate data collection sessions. Comparing differences in mean session values with the standard deviations calculated within each session, it is clear that there was no significant difference between sessions. This is reinforced by the p values all being >0.05.

Table A.2. Comparison of step velocity between sessions (mean [±SD]).

<table>
<thead>
<tr>
<th>Athlete</th>
<th>Session 1 SV (m∙s⁻¹)</th>
<th>Session 2 SV (m∙s⁻¹)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.69 [0.17]</td>
<td>8.65 [0.07]</td>
<td>0.961</td>
</tr>
<tr>
<td>2</td>
<td>8.84 [0.36]</td>
<td>8.89 [0.28]</td>
<td>0.855</td>
</tr>
<tr>
<td>3</td>
<td>9.01 [0.08]</td>
<td>8.99 [0.67]</td>
<td>0.648</td>
</tr>
<tr>
<td>4</td>
<td>8.59 [0.06]</td>
<td>8.52 [0.08]</td>
<td>0.300</td>
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<tr>
<td>5</td>
<td>9.30 [0.02]</td>
<td>9.30 [0.04]</td>
<td>0.716</td>
</tr>
<tr>
<td>6</td>
<td>10.06 [0.17]</td>
<td>10.27 [0.01]</td>
<td>0.355</td>
</tr>
</tbody>
</table>
Table A.3 contains normalised kinematic results for all athletes. Normalised results were used in the lower sections of the kinematic asymmetry profiles presented in Figures 4.3 to 4.12, to allow visual comparison of the differences between sides for different variables.

Table A.3. Bilateral kinematic results for each athlete, results are presented as normalised values as a percentage of the maximum value recorded for both sides by each athlete (mean [± SD]).

<table>
<thead>
<tr>
<th>Athlete</th>
<th>SV</th>
<th>SL</th>
<th>SF</th>
<th>zH_{MIN}</th>
<th>zK_{MAX}</th>
<th>θK_{MIN-FLEX}</th>
<th>θH_{MAX-EXT}</th>
<th>yTD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L-R</td>
<td>R-L</td>
<td>L-R</td>
<td>R-L</td>
<td>L-R</td>
<td>L-R</td>
<td>L-R</td>
<td>L-R</td>
</tr>
<tr>
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<td>[2.37]</td>
<td>[2.43]</td>
<td>[2.37]</td>
<td>[1.31]</td>
<td>[1.55]</td>
</tr>
<tr>
<td>02</td>
<td>95.86</td>
<td>94.21</td>
<td>90.13</td>
<td>93.31</td>
<td>94.00</td>
<td>89.17</td>
<td>96.86</td>
<td>96.21</td>
</tr>
<tr>
<td></td>
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<td>[3.84]</td>
<td>[3.73]</td>
<td>[2.66]</td>
<td>[4.85]</td>
<td>[4.73]</td>
<td>[1.75]</td>
<td>[1.03]</td>
</tr>
<tr>
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<td>97.09</td>
<td>96.53</td>
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</tr>
<tr>
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<td>[1.52]</td>
<td>[1.86]</td>
<td>[0.99]</td>
<td>[2.28]</td>
<td>[1.41]</td>
<td>[1.22]</td>
</tr>
<tr>
<td>04</td>
<td>98.90</td>
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<td>89.08</td>
<td>97.95</td>
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<td>[3.27]</td>
<td>[2.58]</td>
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</tr>
<tr>
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<td>98.20</td>
<td>95.97</td>
<td>94.31</td>
<td>94.46</td>
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</tr>
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<td>93.21</td>
<td>96.26</td>
<td>95.39</td>
<td>91.32</td>
<td>96.72</td>
<td>98.36</td>
</tr>
<tr>
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<td>[1.43]</td>
<td>[2.92]</td>
<td>[2.42]</td>
<td>[2.95]</td>
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<td>[1.71]</td>
<td>[1.45]</td>
</tr>
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<tr>
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<tr>
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<td>[0.76]</td>
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<tr>
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<td>[1.89]</td>
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<td>[0.64]</td>
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<td>[2.12]</td>
<td>[3.18]</td>
<td>[1.45]</td>
<td>[0.92]</td>
</tr>
</tbody>
</table>
Table A.4 contains kinetic results for all athletes as well as KAS values. Support moment and net joint work values are presented as normalised dimensionless values, using the method of Hof (1996).

Table A.4. Mean [±SD] results of kinetic variables for left and right sides and KAS values for each athlete.

<table>
<thead>
<tr>
<th>Athlete</th>
<th>KAS</th>
<th>IMP₁ (N·s)</th>
<th>IMPᵥ (N·s)</th>
<th>Fz_MAX (BW)</th>
<th>M_SUP</th>
<th>WA_NET</th>
<th>WK_NET</th>
<th>WH_NET</th>
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<tbody>
<tr>
<td>R</td>
<td>L</td>
<td>R</td>
<td>L</td>
<td>R</td>
<td>L</td>
<td>R</td>
<td>L</td>
<td>R</td>
</tr>
<tr>
<td>01</td>
<td>19.35</td>
<td>4.51</td>
<td>10.92</td>
<td>188.96</td>
<td>181.55</td>
<td>4.59</td>
<td>4.29</td>
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<td>[10.27]</td>
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<td>200.76</td>
<td>196.22</td>
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<td>3.67</td>
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<td>189.91</td>
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<td>3.74</td>
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<td>[0.02]</td>
<td>[0.19]</td>
<td>[0.039]</td>
<td>[0.100]</td>
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</tbody>
</table>
APPENDIX A.6 – EXAMPLE PARTICIPANT INFORMATION SHEETS AND WRITTEN INFORMED CONSENT FORMS

Ethical approval was gained from the University Research Ethics Committee. Appendix A.6 contains example participant information sheets and a written informed consent form. These forms were provided to all athletes that participated in the studies contained within this thesis. The consent form was used to obtain written informed consent from each athlete prior to their participation in testing.
Participants Information Sheet

Research Project Title: SESAME: SEning for Sport And Managed Exercise: A Multidisciplinary Study of Athletic Performance

Participant Name: .................................................................
Gender: .................................................................
Date of Birth: .................................................................
Event(s): .................................................................
Event PB(s): .................................................................

Name of Researcher (Postgraduate Student): Mr Timothy Exell
Telephone: [REDACTED]
Email: [REDACTED]

Name of Researcher (Project Supervisor): Professor David Kerwin
Participant Information Sheet

**Research Project Title:** SESAME: SEnsing for Sport And Managed Exercise: A Multidisciplinary Study of Athletic Performance

The purpose of this project is to investigate the biomechanical factors that are most important to sprint technique. There is currently little information available that links coaches’ technical knowledge with the available biomechanical information. The purpose of this study, therefore, is to identify how the important biomechanical characteristics of sprinting relate to the technical characteristics that have been identified by elite coaches in a previous study.

Once a comparison of the two sets of information has been performed, a graphical user interface will be developed in order to provide immediate feedback on the biomechanical characteristics of sprint technique to athletes and their coaches during sprint training sessions that are held within NIAC.

**Your Participation in the Research Project**

**Why you have been asked**
We are currently asking skilled athletes who have a background in sprint training to take part in this study. Any current athlete can join the study. It is entirely voluntary – there is no obligation of any kind to join the study, and UWIC will not discriminate in any way against anyone who does not want to take part.

**What happens if you change your mind?**
If you decide to join the study you can change your mind and stop at any time. We will completely respect your decision. If you want to stop it would help us if you could let us know and it will save us bothering you with unnecessary telephone calls. There are absolutely no penalties for stopping.

**What would happen if you join the study?**
If you agree to join the study, data will be collected during a normal sprint training session, typically in the National Indoor Athletics Centre at UWIC. You will be required to perform your own warm up and preparation for the session, which will typically involve no more than six or eight sprint runs. You will be required to perform your own warm down. At the first session, direct measurements of body height and mass will be taken. At one session, a more detailed series of measurements of your body dimensions may be taken.

Data will be recorded using automatic motion analysis sensors, video footage, still photos or a combination of all three. Should motion analysis be utilised then you will be required to wear a series of small, unobtrusive body-mounted sensors for the duration of the training session.

**Are there any risks?**
We do not think there are any significant risks due to this study. The study has not been designed to go beyond the requirements of a normal sprint training session and therefore the risks are no greater than those posed by training.

**Your rights.**
Joining this study does not mean you have to give up any legal rights. In the event of your suffering any adverse effects as a consequence of your participation in this study, you will be compensated through UWIC’s insurance.
Any special precautions needed?
We are asking athletes to perform a physical task and would ask the participant not to deviate from their normal pre-training routines.

What happens to the data collected and pictures taken?
A member of our research team is responsible for putting all the information from the study (except names, addresses and personal identification information) into a computer. This data will form the basis for further processing and analysis. We will try to identify whether the biomechanical parameters recorded can be linked to the essential characteristics of sprint performance identified by the elite coaches.

Are there any benefits from taking part?
There are no direct benefits to you for taking part; however this study may help improve sprint coaching and training by enhancing our knowledge of sprint technique and the development of sport-specific performance monitoring aids.

How we protect your privacy:
All the information we get from you is strictly confidential, and everyone working on the study will respect your privacy. We have taken very careful steps to ensure that you cannot be identified from any of the information that we keep about you.

We keep your personal details completely separate from the other forms that could let anyone work out who you were.

Footage and all personal data will be kept secure, with access only granted to those directly involved in the study, under the rules of the Data Protection Act (1998). Data may be presented in the public domain, but any participant-identifying information will be made anonymous.

______________________
Date
Title of Project: SESAME: SEnsing for Sport And Managed Exercise
Name of Researcher (Postgraduate Student): Mr Timothy Exell
Name of Researcher (Project Supervisor): Professor David Kerwin

Name of Participant …………………………………

Participant to complete this section: Please initial each box.

1. I confirm that I have read and understood the information sheet dated ………………. for the above 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 I am free to withdraw at any time, without giving any reason, without my relationship with UWIC, or my legal right, being affected.

3. I understand that relevant sections of any of the research notes and data collected during the study may be looked at by responsible individuals from UWIC for monitoring purposes, where it is relevant to my taking part in this research. I give permission for these individuals to have access to my records.

4. I agree to take part in the above study.

5. I agree to the taking of photographs or video for publication / presentation purposes. (please tick as appropriate) Yes No

Name of Participant

Signature of Participant _____________________________ Date ____________

Name of the person taking consent

Signature of person taking consent _____________________________ Date ____________
APPENDIX B – COMPUTER PROGRAMS

Analyses of step characteristics, kinematics and kinetics performed in Chapters 3 to 5 were implemented via custom computer programs written in MATLAB (R2009a to R2010a, The MathWorks, USA). Program references are listed in Table B.1. Program scripts are available as document Volume II by request from the Sports Biomechanics Research Group, Cardiff School of Sport, University of Wales Institute, Cardiff, Cyncoed Campus, Cardiff, CF23 6XD, United Kingdom.

Table B.1. Description of MATLAB programs written for data analysis.

<table>
<thead>
<tr>
<th>Program</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>step_char</td>
<td>Processes reconstructed 2D coordinate data from video-based data collection for the analysis of step characteristics. Output variables include step velocity, step length and step frequency for L-R and R-L steps.</td>
</tr>
<tr>
<td>Kinematic_asym</td>
<td>Processes raw CODA 3D coordinate data to calculate segment positions of the lower limbs and subsequent sagittal plane joint angles for left and right ankle, knee and hip joints.</td>
</tr>
<tr>
<td>Kinetic_asym</td>
<td>Processes raw CODA 3D coordinate data and force plate data to calculate force and impulse values. Implements inverse dynamics analysis to calculate joint moment, power and work for left and right ankle, knee and hip joints.</td>
</tr>
<tr>
<td>autocor_CO</td>
<td>Implements the autocorrelation method (Challis, 1999) for the determination of optimal cut-off frequency.</td>
</tr>
<tr>
<td>COP_compare</td>
<td>Processes raw CODA 3D coordinate data and force plate data and calculates displacement between the COP and control point.</td>
</tr>
</tbody>
</table>