KINEMATICS AND KINETICS OF MAXIMAL VELOCITY SPRINTING AND SPECIFICITY OF TRAINING IN ELITE ATHLETES

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NOMENCLATURE AND DEFINITIONS

Symbols used in equations

t	Time (s)
d	Displacement (m)
v	Velocity (m/s)
a	Acceleration (m/s^2)
m	Mass (kg)
g	Acceleration due to gravity (-9.81 m/s^2)
θ	Angular displacement (°)
ω	Angular velocity (°/s)
α	Angular acceleration (°/s^2)
σ	Standard deviation
δ	Mean of difference

Abbreviations used for terminology throughout the thesis

COM	Centre of mass
GRF	Ground reaction force (N)
SL	Step length (m)
SF	Step frequency (Hz)
GCT	Ground contact time (s)
FT	Flight time (s)
LDM	Laser distance measurement
EMG	Electromyography
ROM	Range of motion (°)
2-D	Two-dimensional
3-D	Three-dimensional
PB	Personal best time (s)
BW	Force (N) divided by body weight (N)
RM	Repetition maximum
HK	Hip-knee coupling
KA	Knee-ankle coupling

Fy	Horizontal GRF (N)
Fz	Vertical GRF (N)
I	Impulse
DL	Deadlift
BSq_{drop}	Bulgarian split squat drop
DJ	Drop jump
CMJ	Countermovement jump
RFD	Rate of force development (N/s)
E-RFD	Eccentric rate of force development (N/s)
SLd	System load (N)

Symbols used to abbreviate statistical terminology throughout the thesis

p	p-value
CI	Confidence interval
ICC	Intraclass correlation co-efficient
CRP	Continuous relative phase
CRPv	Continuous relative phase variability
ρ	Spearman's rank order correlation coefficient
R	Pearson correlation co-efficient
R^2	Coefficient of determination
RMSD	Root mean squared difference

Definitions of key terms used throughout the thesis

TO	Toe-off: the first frame in which the foot has visibly lost contact with the ground
TD	Touchdown: the first frame in which the foot is visibly in contact with the ground following the flight phase

D_{TD} Touchdown distance: the horizontal distance between the x-coordinate of the COM and the x-coordinate of the COM of the stance foot at the point of touchdown

D_{TO} Toe-off distance: the horizontal distance between the x-coordinate of the COM and the x-coordinate of the COM of the stance foot at the point of toe-off

MS Mid-stance: the frame in which the x-coordinate of the COM is directly above the x-coordinate of COM of the stance foot

MKF Maximum knee flexion: the frame of maximum knee flexion during stance

MHF Maximum hip flexion: the frame of maximum hip flexion in the flight phase

MSF Movement Specificity Framework

MSR Movement Specificity Ratio

ABSTRACT

Kinematics and kinetics of maximal velocity sprinting and specificity of training in elite athletes

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Maximal velocity sprinting has been studied extensively from a biomechanical standpoint, however little is known of the biomechanics characteristics at sprint velocities that typify elite athletic performance, due to the difficulties in accessing such athletes and collecting data within a competitive environment. Research has investigated the optimal training to achieve such velocities, with a focus on the specificity of training principle. However the specificity of the common training methods of elite sprinters is yet to be investigated from a biomechanical perspective.

Investigations of ten international level sprinters in a competition environment revealed the kinematic variables which characterise sprint velocities exceeding 10.0m/s. Elite sprinters minimised the touchdown distance and knee flexion during ground contact, and terminated stance prior to full extension of the hip and knee. An additional kinetic analysis on six elite male sprinters revealed a greater hip angle at touchdown and higher maximum and average hip velocities in swing were associated with lower peak braking forces. Reduced hip and knee extension at toe-off along with a greater degree of maximum hip flexion were associated with a higher vertical impulse.

A movement specificity framework was developed to quantify the holistic specificity of training methods based on biomechanical movement principles. The Bulgarian split squat drop had a high specificity to maximal velocity sprinting with respect to the loading principles. Running drills were highly specific based on coordination principles, in particular the leg extension velocities in the late phases of stance.

The kinematic and kinetic models can be used by coaches to evaluate individual athletes against true elite sprinting, whilst the movement specificity framework can be utilised to design and maximise the specificity of sprint training programmes.

CHAPTER 1 – INTRODUCTION

1.1 Research overview

Sprinting is of global interest due to the nature of the event in which the human body is pushed to its limits. The aim of sprinting is to cover a set distance in the shortest possible time. During a period of 43 years (1964 to 2007) the 100m world record was reduced from 10.06 to 9.74 s, and since then in a period of 2 years this was improved to 9.58 s which still stands as the current world record. The interest in sprinting has led to large amount of public attention in the event, which is accompanied by an abundance of research in the academic literature. A sprint race is typically divided into three distinct phases: the start, acceleration and maximal velocity phases. The maximal velocity phase typically forms over 50% of the total race distance and the level of velocity attained and maintained during the maximum velocity phase is the factor most highly correlated with performance in the 100 metres (Seagrave, Mouchbahani, & O'Donnell, 2009).

Although research of the maximal velocity phase of sprinting is well documented, the calibre of subjects, and subsequently the range of velocities, is limited and often not indicative of the speeds achieved by elite level athletes. Research on elite athletes is sparse due to the difficulties associated with collecting data, both within training and competition environments. Elite athletes are less willing to have training interrupted for the purpose of data collection, and strict rules at elite levels of competition limit what analysis can be achieved. Collecting data in-competition provides a unique opportunity to investigate elite athletes performing at peak performance level during intense competition. Existing in-competition research tends to focus on the general kinematics associated with sprinting such as stride length and stride frequency without reference to detailed kinematics of technique. Further there is a significant lack of kinetic data relating to maximal velocity sprinting. The existing literature tends to be conducted in laboratories where true maximum velocity cannot be reached, or with the use of treadmills (Morin, Edouard, & Samozino, 2011).

In order to achieve such high horizontal velocities sprinters partake in training programmes. A key principle of training adhered to by coaches is the principle of specificity of training. By applying biomechanical specificity as the basis of training programmes it can positively influence transfer of training, and thus offer a means to improve the effectiveness and time-efficiency of an athlete's preparation (Gamble, 2010). Further it has been shown that as athlete experience increases, the importance of training specificity is heightened, and thus is a key consideration in the design of training programmes for elite athletes. Biomechanical specificity can refer to both kinematic (e.g. angles, range of motion, posture) and kinetic (e.g. mode of muscle contraction, unilateral/bilateral) aspects. Biomechanical specificity has been quantified in gymnastics (Irwin & Kerwin, 2005) and swimming (Payton & Lauder, 1995), but is yet to be researched in track and field.

Therefore the overall aim of this research was primarily to characterise the kinematics and kinetics of maximal velocity sprinting in elite athletes, and secondly to quantify the biomechanical specificity of sprint training methods, with the aim of informing the future training programmes of elite athletes.

1.2 Research questions

To structure the research studies contained within this thesis, five main research aims were developed. In order to assess technique in maximal velocity sprinting and sprint training methods it is necessary to determine the most appropriate methods of data collection. Due to the nature of working with elite athletes data must be obtainable in the training and/or competition environment with minimal interference to the athletes – therefore the validity and reliability of current field-based testing methods were established. Consequently the first research question requiring investigation was:

i. What are the most appropriate measures for analysing the kinematics of maximal velocity sprinting and the associated training methods?

Having identified quantifiable and valid performance measures, different aspects of technique can then confidently be associated with different levels of performance. In order to understand the movement patterns associated with elite maximal velocity sprinting a second research question was developed:

ii. *Which kinematic variables are associated with elite levels of maximal velocity sprinting?*

This will indicate which movement patterns are associated with higher levels of performance, in particular those exhibited by international-sprinters at velocities >10.0m/s; however it provides no information as to how these movement patterns are achieved.

iii. *Which kinetic variables are associated with elite levels of maximal velocity sprinting?*

The use of kinetic analysis in conjunction with kinematic analysis will provide information as to how the kinematic variables associated with maximal velocity sprinting are achieved, therefore the observational study will be extended in order to answer the fourth research question:

iv. *What are the relationships between the kinematics and kinetics of elite maximal velocity sprinting?*

Having established the key performance determinants of elite maximal sprinting performance it is necessary for athletes to try and strive towards attaining these variables. The principle of biomechanical specificity has developed growing interest, suggesting that in order to maximise the efficiency of training the training methods employed should be specific. Yet the interpretation of training specificity is often misunderstood and is based on subjective opinion as opposed to a quantifiable value. Subsequently a fifth research question was developed:

v. *How can specificity be quantified holistically based on biomechanical movement principles?*

Following the development of a framework to quantify specificity the framework will be applied to a selection of training methods utilised by elite athletes in order to answer the sixth research question:

vi. *What is the biomechanical specificity of training methods to maximal velocity sprinting?*

A focus on the biomechanical specificity of running drills and selected strength training exercises to maximal velocity sprinting was investigated for a group of elite athletes. This will aid understanding of the degree of specificity of current training methods to facilitate future programming by coaches.

These six research questions provide a framework around which the thesis can progress. Specific biomechanical investigations were then developed in order to answer each question, which were split into the chapters detailed below.

1.3 Organisation of chapters

1.3.1 Chapter 2 – Review of literature

A review of the literature is provided in Chapter 2. Firstly the review pinpoints a definition of ‘elite sprinting’, which is then used to focus the discussion of existing research on maximal velocity sprinting to that only conducted on elite athletes. The review is split into both kinematic and kinetic research. The specificity of training principle is discussed, particularly with respect to biomechanical specificity. The review then discusses the current maximal velocity sprint training methods employed, covering isolation drills and strength conditioning programmes. Finally the methodological approaches and techniques used to conduct biomechanical investigations are discussed.

1.3.2 Chapter 3 – Assessment of methods used to evaluate maximal velocity sprint running and associated training methods

An investigation was conducted to establish the validity and reliability of data collection methods for maximal sprinting. Due to the nature of the sample being used the methods available to the researcher are limited to those available for use in the training and competitive environment. The aim of this chapter is to establish the reliability and validity of various data collection methods to ascertain whether they can be used interchangeably, and thus will inform the methodology adopted in subsequent chapters.

1.3.3 Chapter 4 – Development of kinematic technical model of maximal velocity sprinting

In order to inform the latter concept of specificity of training it is necessary to initially identify the key technical determinants of maximal velocity sprinting. The aim of this chapter was to identify the kinematics associated with maximal velocity sprinting respectively. It is hypothesised there will be significant technique differences between elite and sub-elite athletes, which based on biomechanical principles will indicate how higher velocities are achieved.

1.3.4 Chapter 5 – Development of kinetic technical model of maximal velocity sprinting

In order to further understand the findings of Chapter 4 a kinetic analysis of maximal velocity sprinting was undertaken in order to associate the external kinetics with elite sprint performance. The relationship between external kinetics and horizontal velocity was determined, and secondly the relationship between external kinetics and associated kinematics was established. It is hypothesised that external kinetics will change with velocity and there will be a relationship between external kinetics and the associating kinematic technique variables.

1.3.5 Chapter 6 – Biomechanical specificity of sprint training

In order for elite athletes to achieve this technical model they undergo periodised training programmes. The training principle of specificity is important to consider for all aspects of training. The aim of this chapter was to develop a method to quantify the specificity of various training methods adopted by elite sprinters, strengthened with objective data of running drills and strength and conditioning exercises. It is hypothesised the running drills will display specificity in joint angular velocity, and that the single-leg squat will display more specificity than the deadlift to maximal velocity sprinting.

1.3.6 Chapter 7 - Discussion

The main findings and practical application of this research is discussed in Chapter 7. The research questions outlined in Chapter 1 are addressed using the results obtained throughout each of the investigations. Limitations of the research are outlined, before potential directions for future research are presented.

CHAPTER 2 – REVIEW OF LITERATURE

2.1 Introduction

In the athletic event of sprinting the aim is to cover the race distance in the shortest possible time, which is achieved by a rapid acceleration to maximal horizontal velocity and sustaining it as long as possible. There is a large discrepancy in subject populations used for research, and in particular the definition of 'elite athlete' populations. Subsequently the initial part of this chapter will aim to identify a definition of elite, which will then dictate the inclusion or exclusion of research from this review. Maximal velocity sprinting has been the subject of a wealth of research and will be discussed from both kinematic and kinetic perspectives. The biomechanical specificity of the training methods adopted to improve maximal velocity sprinting will be addressed, and the final section will consider the data collection methods used in the biomechanical analysis of maximal velocity sprint running. The review of the literature led to the development of research questions that guided the studies contained within Chapters 3 - 6.

2.2 Biomechanics of maximal velocity sprint running

2.2.1 The difficulty in defining 'elite'

Research on maximal velocity running (sprinting) has been existent for almost a century e.g. Fenn (1930). Due to the relative ease of data collection descriptive kinematic variables have been well documented for a range of running speeds between 5 and 9m/s. However an elite sprinter can reach a maximal speed of over 12m/s (Mann, Kotmel, Herman, Johnson, & Schultz, 1984) and thus conclusions from such data are not representative of true elite performance. The literature concludes there any many factors that determine an athlete's success in the 100m sprint, including physiological, morphological and anatomical aspects – along with the technique element of maximal velocity sprinting (Baechle, Earle, & Wahten, 2000). An elite sprinter will have an optimal combination of each of these elements to produce a high maximal horizontal velocity.

Although research has seemingly been published on elite athletes the difficulty arises when trying to decipher how authors have defined the term ‘elite’. The Segens Medical dictionary definition of an elite athlete is ‘a person who is currently or has previously competed as a varsity player (individual or team), a professional player or a national or international level player’. This notion is reflected by the majority of sporting research utilising elite athletes (not limited to track and field) who describe their research as using elite athletes from either national or international competition. Yet this already covers a wide scope of athletes; a 100m sprinter from the heats of the Croatian national track and field championships (Vucetic, Matkovic, & Sentija, 2008) is unlikely to be comparable to the first place finisher at an Olympic Games (Mann & Herman, 1985), yet both are defined as ‘elite’ by the authors. In contrast Cook, Crewther, and Smith (2012) used the division between national and international level to define non-elite and elite athletes respectively. Often when data is collected from international competitions (e.g. Olympic Games/World Championships) the sample is automatically defined as elite e.g. Nolan, Patritti, and Simpson (2006); Tamminen, Holt, and Neely (2013), however such competitions can often include a large range in ability based on countries individual qualifying standards. The variation in subject information reported by authors often makes it difficult to compare research. In some cases authors state the personal best times of the sample as their evidence of elite athlete status, however this gives no indication of how they perform on the date of the research. For example Morin et al. (2012) used an athlete with a 100m personal best time of 9.96 seconds for their research, however during testing the athlete only achieved speeds of 8.66m/s. A more useful measure would be to report the race time achieved on the day of the testing – however this is only appropriate when data is collected within a competition environment. The 100m-time is directly related to the horizontal velocity of the centre of mass (COM), and therefore the maximal horizontal velocity achieved during the testing may be the best indication of performance (and subsequently athlete status). However not all research reports the maximal velocity due to the difficulties of obtaining instantaneous speed measures. Often only an average horizontal velocity over the full testing and/or competition distance is provided. Likewise calculating velocity from stride length and stride frequency measures (as reported by some research) only provides an average velocity over each individual step.

As the kinematics and kinetics of maximal velocity sprinting are directly related to horizontal velocity it is proposed that for the literature review a minimum horizontal velocity is defined before the subject population can be classified as ‘elite’. This will enable the researcher to focus solely on elite athlete research; readers interested in a greater scope of speeds are directed to the research of Mero, Komi, and Gregor (1992) and Novacheck (1998). The minimal horizontal velocity identified is based on the current literature and the horizontal velocities achieved by top-level sprinters. To maintain consistency throughout the thesis it was decided that the minimum horizontal velocity to meet the classification of an ‘elite’ athlete would be 10.0m/s. Where only 100m-time is reported a regression equation will be used to estimate the maximal horizontal velocity achieved. In order to produce this regression equation, 100m data from the 2009 World Championships in Berlin was used to examine the relationship between overall 100m-time and velocity achieved in different stages of the race. A research project by the German Athletics Federation reported the 100m times and 20m segment times for all athletes in all 100m races of the competition from heats through to the final (n=122). For the purpose of the current research the 20m segment between 60-80m was identified as most relevant as this was where the majority of the athletes ran their quickest 20m segment. By dividing the distance (20m) by the interval time for this segment an average horizontal velocity can be calculated for this stage of the race. Whilst this is still only an average velocity it is a better indication of maximal velocity than velocity averaged over the whole race as it excludes the start acceleration and deceleration phases of the race. Table 2-1 indicates the spread of 100m times, and the associated average horizontal velocities achieved within the 20m segment between 60 and 80m. Secondly the 100m-time was plotted against the average horizontal velocity for 60-80m to develop an equation from which horizontal velocity can be predicted from the overall 100m times (Figure 2-1). The regression equation explains 85% of the association between 60-80m velocity and 100m time however 15% still remains unexplained. This 15% may be attributed to elements of the race nearer the start, for example reaction time and the acceleration phase.

Table 2-1 Mean (±SD) 100m time (s), 60-80m split (s) and average velocity (m/s) for all competitors in the 100m at the 2009 World Championships (German Athletics Federation)

100m time category	n	100m time (s)	60-80m time (s)	Average velocity between 60-80m (m/s)
9.50-9.59	1	9.58	1.61	12.42
9.60-9.69	0	N/A	N/A	N/A
9.70-9.79	1	9.71	1.63	12.27
9.80-9.89	2	9.87 (0.04)	1.69 (0.01)	11.83 (0.10)
9.90-9.99	9	9.95 (0.02)	1.70 (0.01)	11.78 (0.10)
10.00-10.09	12	10.03 (0.03)	1.72 (0.01)	11.62 (0.09)
10.10-10.19	15	10.16 (0.02)	1.73 (0.02)	11.54 (0.13)
10.20-10.29	27	10.24 (0.03)	1.77 (0.02)	11.32 (0.11)
10.30-10.39	27	10.35 (0.03)	1.80 (0.03)	11.12 (0.17)
10.40-10.49	16	10.43 (0.03)	1.82 (0.03)	11.00 (0.17)
10.50-10.59	11	10.56 (0.06)	1.85 (0.03)	10.80 (0.18)
10.60-10.69	0	N/A	N/A	N/A
10.70-10.79	1	10.71	1.85	10.81
TOTAL	**122**	**10.26 (0.19)**	**1.77 (0.05)**	**11.29 (0.35)**

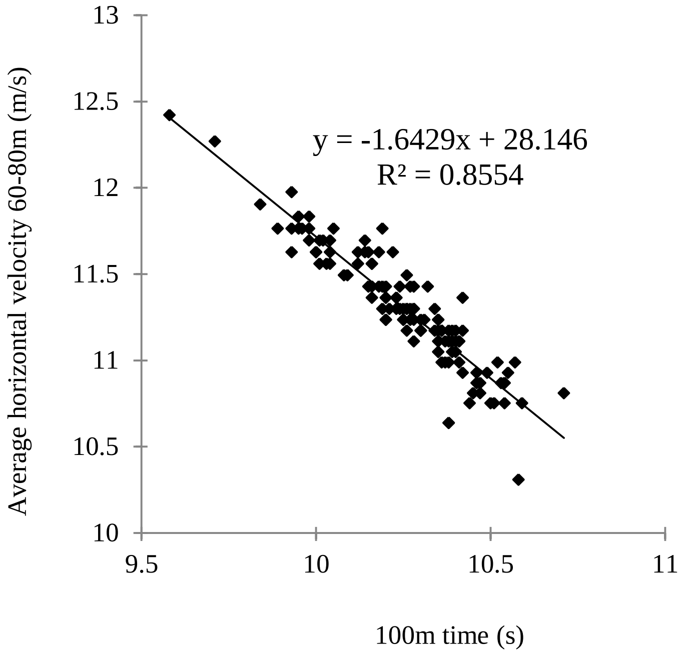


Figure 2-1 Correlation between average horizontal velocity (m/s) from 60-80 and total100m time (s) and the regression equation

Along with a minimum horizontal velocity that must be reported (10.0m/s) there are further criteria that must be satisfied to warrant inclusion in the literature review. The research must specify the use of track and field athletes, and specifically specialists in either the 100m or 200m races. Races covering a further distance are subject to the effects of fatigue, which may alter kinematic and/or kinetic data.

2.2.2 Descriptive kinematic research

To gain an understanding of the kinematic variables which govern maximal velocity sprinting Hay (1993) developed a ‘deterministic model’ to explore the interactions of different variables and their relative influence on maximal velocity. This deterministic model has more recently been adapted by Hunter, Marshall, and McNair (2004a), and provides a framework of how maximal velocity is achieved (Figure 2-2). Maximal velocity sprinting is defined biomechanically as the product of step frequency (SF) (or step rate) and step length (SL) (Hay, 1993), where in order to achieve maximum sprint velocity the optimum combination of SL and SF must be achieved. A step is defined as the distance between successive points of contact of the opposite feet, whereas a stride is the distance between successive points of contact of the same foot, and subsequently a stride is the sum of two consecutive steps.

A summary of the research which has investigated the kinematics of maximal velocity sprinting at velocities >10.0m/s is presented in Table 2-2. Due to the ease of data collection the mostly commonly reported variables are SL and SF and a wealth of data exists regarding these variables in elite athletes.

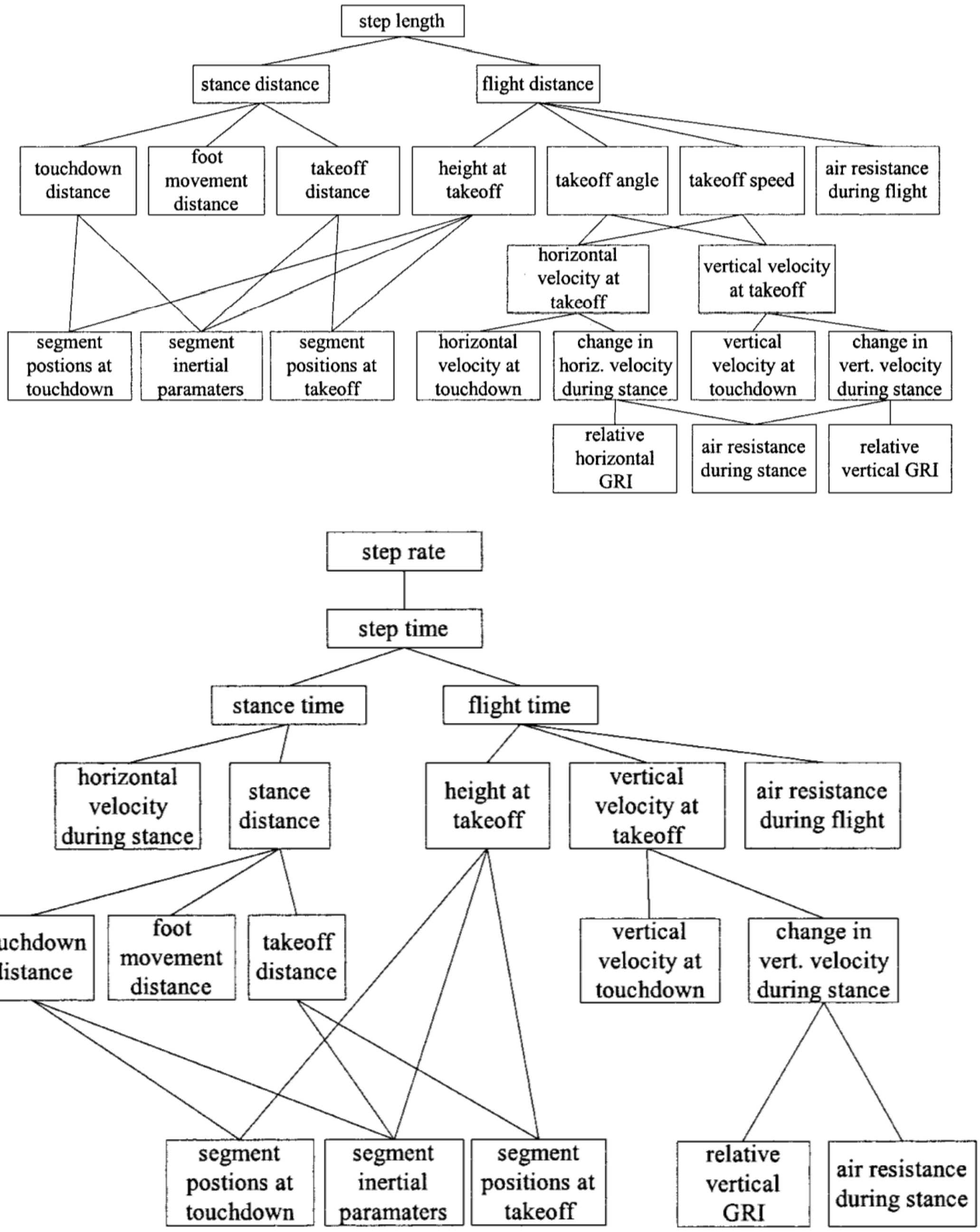


Figure 2-2 Deterministic model of sprinting (Hunter, 2004)

The earliest research to report SL and SF data for elite athletes was Kunz and Kaufmann (1981) who aimed to established critical factors of maximal sprinting by comparing world class sprinters to decathletes during a 100m competitive race. This serves as a comparison between elite and non-elite sprinters as whilst the decathletes are competing in international competition they are not 100m or 200m specialists. The 100m-time for decathletes ranged from approximately 10.8 – 12.1 seconds and from 10.0 – 10.5 seconds for the elite sprinters (exact times not specified). Using the regression equation developed earlier in the chapter it can be estimated that the elite sprinters were achieving a maximal velocity >10.0m/s between 60-80m. Four strides were recorded at the 70m point of the race which represents the phase of maximal velocity. The elite sprinters exhibited both a greater SL (2.58m) and SF (4.62Hz) in comparison to the decathletes, which suggests it is an optimal combination of SL and SF which leads to improved 100m sprint time rather than a specific increase in either one or the other. However as only scatterplots of the full sample are reported rather than individual data it is not possible to consider the interrelationship between the two variables.

Mann and Herman (1985) also collected data from elite athletes in competition which maximises the external validity of the findings. The authors compared the 1st and 8th place finishers in the 200m final at the 1984 Olympic Games to ascertain which kinematic variables were critical to maximal velocity sprinting. Once again this allows a comparison of an elite vs. non-elite sprinter as the horizontal velocity achieved by the 1st place finisher was 10.21m/s whereas the 8th place finisher only achieved a velocity of 9.29m/s. A camera was placed at 125m into the race to identify the SL and SF at the maximal velocity phase of the race. The first place finisher (200m time: 19.80s) had a SL of 2.38m and SF of 4.30Hz, whereas the 8th place finisher (200m time: 20.85s) had a SL of 2.31m and a SF of 4.01Hz. This corresponds with the findings of Kunz and Kaufmann (1981) that greater horizontal velocities are accompanied by an increase in both SL and SF. However the 2nd place finisher (200m time: 19.96s) had the same SL as the 1st place finisher (2.38m), yet the SF was lower at 4.01Hz, which suggested that SF is the most critical factor to achieving higher sprint velocities. Both the previous aforementioned studies only used three elite sprinters for their analysis and thus it is difficult to establish a pattern of SL and SF and whether it is individually biased.

Coh, Mihajlovic, and Praprotnik (2001) compared two groups of elite sprinters to identify the relationship between SL and SF to maximal velocity. Group A consisted of 10 elite sprinters with an average 100m PB of 10.52s and Group B (also defined as 10 elite sprinters) had an average 100m PB of 11.09s. Group A and Group B achieved velocities of 10.22m/s and 9.73m/s respectively which is similar to the speeds observed by Mann and Herman (1985). These velocities indicate that whilst the authors define Group B as elite, based on the classification set earlier in this thesis Group B actually represent a sub-elite sample. The SF values were similar to those already reported in the literature (Group A: 4.64/Group B: 4.49Hz), however the SL values were less (Group A: 2.21/Group B: 2.17m) than reported by Kunz and Kaufmann (1981) and Mann et al. (1984). When comparing Group A to Group B it was found that whilst 100m PB time and running velocity were significantly different between the groups neither SL nor SF were significantly different. This may be due to the large standard deviations (and thus large variation) between athletes which masks the possible relationships between SL and SF. It is proposed it may be the interrelationship between SL and SF that has more impact on horizontal velocity as opposed to the values in isolation.

Ae and colleagues (Ae, Ito, & Suzuki, 1992) reported SL and SF data for the top eight finishers of the 100m final at the 1991 World Championships. During the maximal velocity phase of the race (70-80m) where an average speed of 11.70m/s was achieved the average SL and SF across the eight finalists was 2.56m and 4.57Hz respectively. Paruzel-Dyja, Walaszczyk, and Iskra (2006) used competition data from the 2003 World Championships to compare the SL and SF of 109 male sprinters during the 100m races (heats, semi-finals and finals). Although horizontal velocity was not reported, using 10.15s as the average 100m-time for the ‘faster’ males the regression equation developed earlier predicts a horizontal velocity of 11.47m/s. The ‘faster’ males displayed an average SL of 2.19m and SF of 4.49Hz. This is a considerably smaller SL than reported from previously mentioned studies, yet this is because SL values were averaged over the entire race. Similarly methodological differences between the studies such as sampling rate and the method used to calculate stride length limit true comparisons. Surprisingly the correlations found that for elite male sprinters stride length was significantly correlated with 100m-sprint time, whereas stride frequency showed no significant correlation. However the results of the correlations should be treated with caution as they are correlated to overall 100-m time and subsequently take into account the reaction time, start and acceleration phase of an athlete's race as well as the maximal velocity phase. Furthermore using a correlation with an elite population is limited as there is minimal variation in stride frequency and stride length between athletes, and therefore correlations will be weak.

All aforementioned research has measured elite athletes at one point in time, either in one competition or over an average of three runs within a laboratory. To gain a better understanding of elite athletes SL and SF patterns Salo, Bezodis, Batterham, and Kerwin (2011) studied a sample of 11 elite male sprinters over a number of races (minimum 10 races per athlete) to establish whether they were SL or SF reliant. Similar to Paruzel-Dyja et al. (2006) both SL and SF were correlated to 100m-time as horizontal velocity data was not available. Salo et al. (2011) observed a large variation between the 11 athletes regarding SL or SF dominance and concluded it is a highly individual occurrence. There was a negative interaction between SL and SF, for example athletes with a greater SL had a lower SF and vice versa.

Table 2-2 Summary table of research investigating kinematics of elite maximal velocity sprinting (>10.0m/s). *Italics indicates the variable has been indirectly calculated*

Study	Sample	Phase of analysis	Horizontal Velocity (m/s)	100m time (s)	Step length (m)	Step frequency (Hz)	Ground contact time (s)	Flight time (s)
Kunz and Kaufmann (1981)	3 international male sprinters	4 strides at 70m	*11.92*	10.13	2.58	4.62	0.076	*0.141*
Mann et al. (1984)	15 male sprinters		*11.02*		2.32	4.75		
Mann and Herman (1985)	2 male sprinters	2 strides at 180m	10.82		2.48	4.35	0.100	0.130
			10.29		2.49	4.17	0.110	0.110
IAAF Biomechanics Research (1988)	7 male sprinters at 1988 Olympic Games	Average over 100m	*10.01*	9.99	2.23	4.49		
		Average 60-90m	*11.48*		2.50	4.59		
Vardaxis and Hoshizaki (1989)	2 male sprinters	1 stride at 55m	10.15	10.59	2.40	4.27		
			10.32	10.69	2.38	4.30		
Ito et al. (1994)	1 international male sprinter (CL)		*11.82*	9.86	2.53	4.67		
IAAF Biomechanics Research (1997)	6 male sprinters at 1997 WC	Average over 100m	*10.03*	9.96	2.18	4.6		
		Average 60-100m	*10.90*		2.35	4.64		
Coh et al. (2001)	12 male sprinters	20m with flying 20m	10.22	10.52	2.21	4.64	0.090	0.126
Paruzel-Dyja et al. (2006)	109 male sprinters at 2003 WC	Average over 100m race	*9.83*	10.15	2.19	4.49		
			9.54	10.46	2.14	4.46		
Ito, Ishikawa, Isolehto, and Komi (2006)	18 male sprinters at 2005 WC	1 stride at 60m	11.20	10.22	2.45	4.50		
			10.80	10.65	2.30	4.50		
Mafákala (2007)	8 male sprinters at 1991 WC	Average at 80m	11.70	9.97	2.56	4.57		
IAAF Biomechanics Research (2007)	5 male sprinters at 2007 WC	Max speed	11.70	9.99				
Bezodis, Kerwin, and Salo (2008)	100m male sprinter	2 strides at 45m	10.26	N/A	2.21	4.65	0.096	
	Decathlete		10.10		2.29	4.41		
Ito et al. (2008)	2 international male sprinters at 2007 WC (TG & AP)	2 strides at 60m	11.85	9.85	2.42	4.90		
			11.88	9.96	2.40	4.96		
IAAF Biomechanics Research (2009)	8 male sprinters at 2009 WC	60-80m	*11.90*	9.92	2.51	4.74		
Salo et al. (2011)	11 elite male sprinters	Average over 100m race	*10.36*	10.12	2.20	4.71		
IAAF Biomechanics Research (2011)	7 male sprinters at 2011 WC	Average 0-100m	*10.59*	10.17	2.54	4.17		
	2011 WC 100m winner (YB)	Max speed	11.75	9.92	2.38	4.65		

In order to further investigate the significance of SL and SF to maximal sprint velocity it is necessary to consider the variables that dictate SL and SF by referring back to the deterministic model (Figure 2-2). Step length is a sum of stance distance and flight distance, of which stance distance is the sum of touchdown distance (D_{TD}) and toe-off distance (D_{TO}) (Figure 2-3), which is governed by the segmental positions (and their associated inertial parameters) during ground contact. During flight the human body acts as a projectile and is only under the influence of gravity, and thus the distance this projectile (COM) moves (i.e. flight distance) is governed by the take-off parameters; height, angle and speed of take-off. Speed of take-off can be divided into both its vertical and horizontal components. Step frequency is calculated as 1/(GCT+FT), where GCT is the ground contact time and FT is the flight time. GCT is determined by horizontal velocity of the body during ground contact and the distance over which it must travel (D_{TD} + D_{TO}). Flight time is governed by the relative height of COM between TO and TD and speed of take-off.

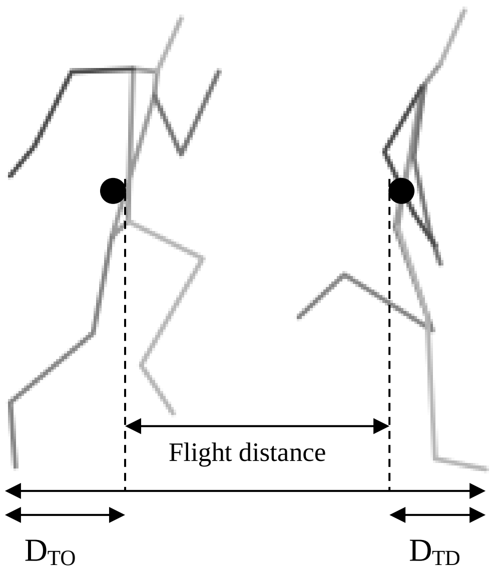


Figure 2-3 Definition of flight distance and stance distance (D_{TO} + D_{TD})

These more detailed kinematic variables are less commonly reported in the elite athlete literature compared to SL and SF as they are harder to measure from basic camera footage. To obtain accurate distances, timings, angles and speeds it often needs additional cameras and/or high-speed cameras, which are not always feasible in a competition environment.

As previously mentioned Coh et al. (2001) found that SL and SF were not significantly different between two groups of elite athletes, however they found that Group A had a significantly shorter GCT (0.089s) compared to Group B (0.095s). In contrast there was no significant difference between the flight times of 0.126s and 0.127s for Group A and B respectively. For the 1st and 8th place finishers at the 1984 Olympic Games the GCT were 0.100s and 0.130s respectively, and flight times were 0.130s vs. 0.120s (Mann & Herman, 1985). The longer ground contact times than reported by Coh et al. (2001) can be attributed to the fact Mann and Herman (1985) were investigating a 200m race and therefore horizontal velocity was lower. The similar flight times between the 1st and 8th place finisher support the findings of Coh et al. (2001) that differing levels of sprinters actually have similar flight times regardless of ability.

In an aim to explain the differences between SL and SF for world-class sprinters and decathletes Kunz and Kaufmann (1981) reported some further kinematic variables. World-class sprinters had a smaller thigh angle (Figure 2-4) at touchdown, which reduced the stance distance and subsequently led to a reduced ground contact time. Further they had a greater stride landing angle and a greater average acceleration of the thigh, allowing the swing leg to recover quickly to reduce flight time, and subsequently explains the increase in SF. However data were only collected at 100fps, and the authors report relatively large error values for ground contact time (10%) and thigh angle at TD (15%) and therefore comparisons to this data is limited.

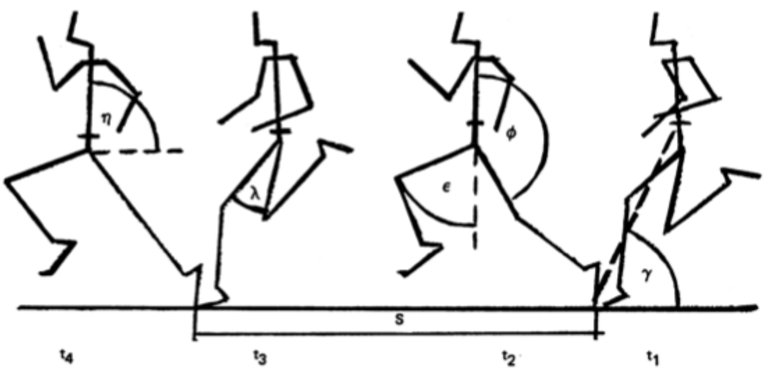


Figure 2-4 Angle definitions used by Kunz & Kaufman (1981). λ = thigh angle. ϒ = stride landing angle. ε = average angular acceleration of the thigh.

From a comprehensive list of upper and lower body kinematics (angle definitions described in Figure 2-5 and Figure 2-6) Mann and Herman (1985) identified the following variables as critical to sprint success (the values for the 1st place finisher vs. the 8th place finisher are reported in brackets): upper leg angle at take-off (167/167°), upper leg velocity during support (-429/-328°/s), lower leg velocity at touchdown (-330/-150°/s), D_{TD} of the foot relative to the body (0.22/0.33m) and relative foot velocity at touchdown (-7.93/-6.47m/s).

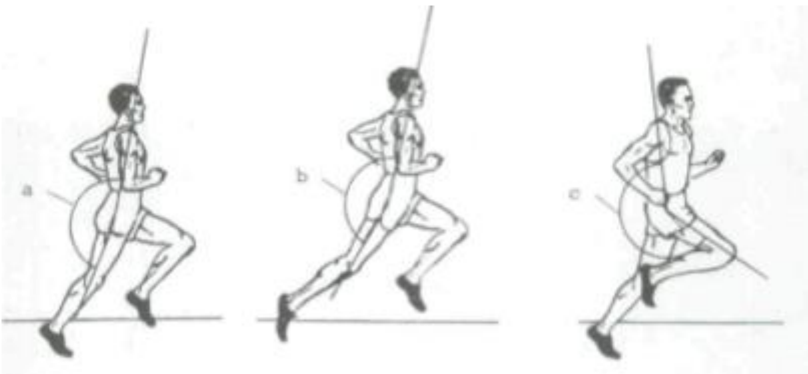


Figure 2-5. Upper leg angle definitions used by Mann & Herman (1985) and Mann (2010). (a) = upper leg angle at toe-off. (b) = upper leg angle at full extension. (c) = upper leg angle at full flexion. Images taken from Mann & Herman (1985).

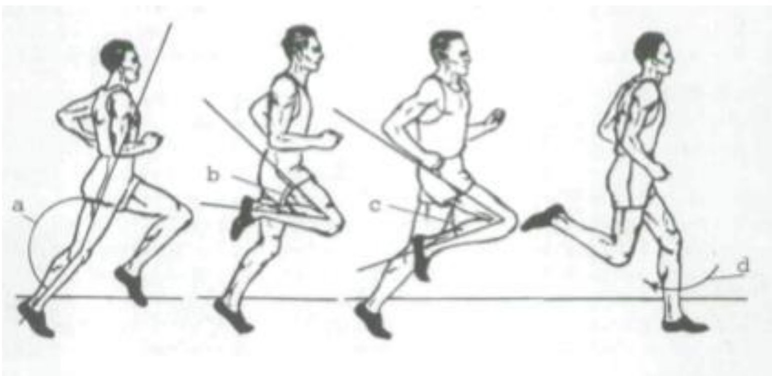


Figure 2-6 Lower leg angle definitions used by Mann & Herman (1985) and Mann (2010). (a) = lower leg angle at toe-off. (b) = lower leg angle at full flexion. (c) = lower leg angle at ankle cross position. (d) = foot speed at touchdown. Images taken from Mann & Herman (1985).

Whilst valuable data as it was the first of its kind conducted on elite athletes, the findings must be treated with caution as they are based on only two individuals. As already discussed SL and SF are individually reliant, and thus this may be the case for the kinematic variables that dictate them. Mann's research in 1984 included a greater sample size of 15 male and 20 female elite sprinters, and since then he has collected data over a period of years, of which the findings have been published in a book (Mann, 2010). Mann (2010) reported expected values for 'poor', 'average' and 'good' sprinters, of which the horizontal velocity ranges are 11.25m/s, 11.90m/s and 12.55m/s respectively. It is worth noting at this stage that a 'poor' sprinter as defined by the author is still classified as elite based on the criteria defined in this thesis, and thus Mann's research should be used as a comparison amongst the very top athletes. The data gives an indication of expected values for elite athletes, and a comparison of 'good' to 'poor' sprinters demonstrates whether a greater or lesser value is advantageous. Table 2-3 provides a summary of the main findings.

Table 2-3 Kinematic data of 'good', 'average' and 'poor' sprinters (Mann, 2010). Angle definitions described in Figure 2-5 and Figure 2-6.

Kinematic variable	'Good'	'Average'	'Poor'
Horizontal velocity (m/s)	12.55	11.90	11.25
Stride length (m)	2.70	2.63	2.56
Stride frequency (Hz)	4.83	4.53	4.43
Ground contact time (s)	0.087	0.094	0.101
Flight time (s)	0.123	0.118	0.128
Time to maximum upper leg flexion (s)	0.033	0.023	0.013
Upper leg angle at toe-off (°)	170	160	165
Upper leg angle at full extension (°)	165	160	155
Upper leg angle at full flexion (°)	260	255	250
Lower leg angle at toe-off (°)	150	155	160
Lower leg angle at full flexion (°)	40	35	30
Lower leg angle at ankle cross position (°)	60	65	55
Foot speed at touchdown (m/s)	8.47	7.59	6.71

As a 'poor' sprinter is classified as running at an average horizontal velocity of 11.25m/s this is greater than the majority of the currently published research and therefore comparisons of values are limited. This published data lacks information regarding when and how it was collected. The definition of a 'good' sprinter specifies a velocity of 12.55m/s however this has rarely, if ever, been achieved. In the 100m-world record race (9.58s) the 20m segments for Usain Bolt indicate the maximum average velocity of 12.42m/s was achieved between 60-80m, however instantaneous velocity was not reported and subsequently it cannot be confirmed he reached a velocity of 12.55m/s. Furthermore there appears to be a lack of scientific rationale behind the selection of variables for analysis, for example the use of the 'ankle cross' position or the 'time to maximum upper leg flexion'.

Currently all research mentioned has only looked at associations between kinematics and horizontal velocity and has failed to perform any statistical analysis on the relationships between the two. Although conducted on female sprinters at lower horizontal velocities (average horizontal velocity 8.06m/s) Coh, Jost, and Stuhec (1998b) reported a number of kinematic variables and their subsequent correlation with maximal velocity. The variables that were significantly correlated to maximal sprint velocity were flight time, ground contact time, velocity of the swing leg and angular velocity of the thigh during propulsion. By referring to the deterministic model it can be identified that each of these significant variables influence step frequency. Whilst the raw data cannot be compared to the elite athlete literature it is proposed that perhaps the relationships between kinematics and horizontal velocity are the same regardless of the magnitude of velocity, and warrants further investigation of these relationships at velocities exceeding 10.0m/s.

All the above research tends to report the joint kinematics at key positions within the stride, for example touchdown and toe-off. An understanding of the joint and limb kinematic profiles for the entirety of a stride is fundamental in gaining a full insight into the technique developments required to enhance performance. Further to this the notion that movement patterns used in sprint running may be determined by a combination of joint couplings as opposed to joints in isolation was proposed by Hunter, Marshall, and McNair (2004c). Despite this, limited understanding of the joint couplings in sprint running currently exists. Pohl, Messenger, and Buckley (2007) reported differences in the coupling motions between walking and running, and thus the findings cannot be extrapolated to sprint running. Gittoes and Wilson (2010) investigated the intralimb joint coordination patterns in sprint running. Two couplings of the lower limb were selected for analysis; the hip-knee coupling (HK) and the knee-ankle coupling (KA). The authors used continuous relative phase (CRP) to quantify intralimb coordination and concluded the KA coupling was more out of phase than the HK coupling and the TD position was more out-of–phase than the TO position. In-phase motion indicates the joints are moving in the same direction and out-of-phase motion indicates the joints are moving in opposing directions. Out-of-phase motion has previously been associated with transitions in the gait cycle, for example from swing to stance (Hamill, van Emmerik, Heiderscheit, & Li, 1999).

An insight into the lower limb joint coupling motions of sprint running would enhance understanding of the task-specific movement patterns associated with high level sprint performance. However the role of variability within joint coordination has been disputed. Dierks and Davis (2007) reported variability was associated with a decrement in locomotive performance, whilst (Hamill et al., 1999) proposed a more variable coupling motion allowed different movement strategies to be adopted to reduce the stress placed on lower extremity structures. Possessing movement variability is important in skills where the adaptability of complex motor patterns is necessary within dynamic performance environments, for example sprinting (Button et al., 2006). The role of variability with respect to differing skill level has been investigated in gymnastics (Busquets et al., 2013) and swimming (Seifert et al., 2010). Traditionally it was thought variability would be detrimental to performance, though Trezise, Bartlett, and Bussey (2011) found better sprinters actually had a higher level of coordination variability and thus some variability may be necessary for success. Bradshaw, Maulder, and Keogh (2007) suggested that flexible coupling motion is associated with a high standard of performance in the sprint running start. Due to the low sample size (and thus low variance in horizontal velocity) Gittoes and Wilson (2010) were unable to investigate the role of variability with respect to skill in maximal velocity sprinting.

The KA coupling was more out-of-phase with respect to the HK coupling but displayed lower variability in the stance phase. Touchdown displayed more variability than toe-off and it was proposed that a destabilisation of the lower limb coordination was necessary at TD to allow for the swing-to-stance transition. The authors only investigated the swing phase until the point of TD of the contralateral limb and therefore negate the full swing phase for the swing limb. The contribution of the swing leg to propulsion in sprint running is largely unknown and therefore warrants a detailed investigation of this phase (Hunter, Marshall, & McNair, 2005). Furthermore the velocities recorded were below that of elite sprint performers (>10.0m/s).

Whilst the SL and SF of elite athletes is well documented (Table 2-2) the lack of experimental research regarding the techniques adopted by elite athletes necessitates further investigation. Whilst the research by Mann (2010) is extensive the velocities reported (11.25-12.55m/s) are at the top end of the spectrum and could be argued not representative of actual elite performance based on the velocities achieved during competition as illustrated in Table 2-2. Furthermore the lack of biomechanical justification for the selection of variables (e.g. the ankle cross position) means the values reported are not associated with how an increase in velocity would be achieved i.e. the kinetics of maximal velocity sprinting.

2.2.3 Descriptive kinetic research

Having established the kinematic variables associated with maximal velocity sprinting the next stage is to identify the causes of the kinematics, namely the kinetics of maximal velocity sprinting. Due to the requirement of force data, kinetic research is much less common than kinematic research. Although several studies have been published detailing kinetics in sprinting they tend to focus on the start (Slawinski et al., 2010) and acceleration (Hunter et al., 2005) phases of the sprint, and use athletes of varying ability not representative of elite athletes. The kinetics of the maximal velocity phase of sprinting can be divided into a) the external kinetics that affect the body during the ground contact phase (ground reaction force and impulse), and b) the internal kinetics that affect the segmental orientation of the body throughout the ground contact phase and flight phase (joint moments). A summary of the research that has investigated the external kinetics of maximal velocity sprinting is presented in Table 2-4. Due to the lack of kinetic research at velocities >10.0m/s the research included in this section of the review was extended to include velocities >8.0m/s.

To this authors knowledge the only research to report kinetic data of overground sprinting at velocities greater than 10.0m/s was conducted by Bezodis et al. (2007) and Bezodis, Kerwin, and Salo (2008). Although the focus of the research was the study of internal joint moments the authors also reported the maximum GRF. For the fastest athlete within the sample (10.37m/s) the peak vertical GRF was approximately 3240N, which when represented relative to athletes bodyweight equated to 4.39BW. For the remainder of the sample (n=3) (average horizontal velocity 9.65m/s) the mean maximum GRF was 3.91BW. The force plate was placed at 45m and research has indicated that maximum velocity is not achieved until 65m and therefore this research may not reflect true maximal velocity sprinting. However the velocities reported in this research are still the greatest available in the peer-reviewed literature. Whilst only a small sample size it suggests that greater velocities are associated with greater GRF, yet this is only peak GRF and does not describe the GRF profile of the ground contact as a whole.

Korhonen et al. (2010) investigated the variability and symmetry of force platform variables at maximal velocity for a sample of 18 100, 200 and 400m runners. Vertical and horizontal GRF's and step temporal-spatial variables were measured during the maximum speed phase of 60m trials using a 9.4m long force platform embedded in the running surface. The mean maximal velocity recorded was 9.50±0.42m/s. The peak vertical GRF recorded was 3.34±0.25 BW, and the average Fz was for the entire ground contact was 2.07±0.13 BW. The peak braking force was 1.42±0.17 BW. Unfortunately the authors fail to report the respective impulses, although the GCT of 0.102s is similar to the literature. This research has the advantage of providing a GRF profile for an entire stride for an individual running at 10.0m/s, along with a Pedotti diagram to illustrate the changes in magnitude and orientation of the resultant GRF throughout the contact (Figure 2-7).

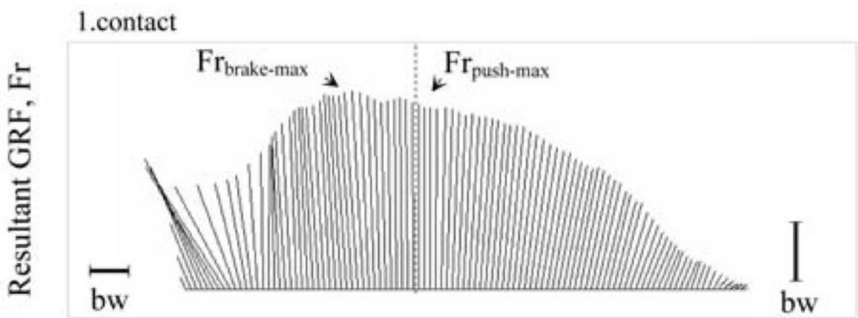


Figure 2-7 Pedotti diagram of a young sprinter at 10.0m/s (Korhonen et al., 2010)

Weyand, Sternlight, Bellizzi, and Wright (2000) conducted a study to identify whether faster running speeds are achieved by greater GRF (kinetics) or more rapid leg movements (kinematics). An instrumented treadmill was used to investigate the kinematics and kinetics of 33 subjects sprinting over various speeds. The fastest speed recorded was 11.1m/s which, based on existing criterion, is indicative of an elite sprinter. This was compared to slower subjects (6.2m/s) to identify the mechanisms available to reach faster top speeds. Regression equations identified neither stride frequency nor stride length to be critical to achieving greater velocities. As maximal velocity increased vertical impulse decreased; however this was attributed to a decrease in contact time rather than a decrease in GRF. The predominant mechanism to reach faster speeds was to apply greater vertical forces to the ground as opposed to increasing the speed of the swing limb. When corrected relative to bodyweight the GRF was 1.26 times greater for a runner with the top speed of 11.1m/s in comparison to a runner at 6.2m/s. The regression equation indicated that increasing the support force by only $1/10^{th}$ of a BW is sufficient to increase top speed by 1m/s. However this data was collected using a treadmill which has been shown to alter the kinematics, predominantly by lengthening the ground contact time and increasing the speed of hip extension during stance (McKenna & Riches, 2007).

At maximal velocity the aim is to maintain horizontal velocity, and subsequently the net horizontal impulse should be zero (as the athlete is neither accelerating nor decelerating). This is evident in the research by Mero and Komi (1994) who found a net horizontal impulse of zero in seven sprinters due to equal braking and propulsive impulses of 20Ns. Kyrolainen, Komi, and Belli (1999) collected force data during overground running and found both the peak forces and rate of force production increased with increasing speed. The maximum vertical force increased from 1665 to 2134N and horizontal force from 235 to 675N as speed increased from 3.25m/s up to the individual maximum (8.23m/s). The authors used a regression analysis to reveal that the net resultant force and its direction of application primarily determined the running speed. In contrast Kuitunen, Komi, and Kyrolainen (2002) found peak Fz was constant but peak Fy increased both in the propulsive and braking phase as speed increased from 70-100% of maximal speed, which reflected a range of approximately 7.00-9.73m/s in their sample. This is contrast to the common in notion that the minimisation of braking forces is important for elite sprinting (Mann, 1981). Despite this very little research reports braking forces in isolation. Morin et al. (2012) used three national-level sprinters and a world-class sprinter to identify the mechanical determinants of a world-class sprinter. Although a world-class sprinter the individual only achieved a maximum velocity of 8.66m/s in the study which has been attributed to the limiting factors of using a treadmill for the analysis. The maximum Fz for this subject was 1657N (2.07BW) and Fy 314N (0.40BW). The authors performed correlations between the mechanical variables of sprint kinetics and 100-m performance variables. In contrast to Weyand et al. (2000) Fy displayed a greater correlation to maximal speed (0.773) than vertical GRF (0.593), however these were GRF values for the entire acceleration phase as opposed to the GRF values at the point of maximum velocity. When the theoretical maximal horizontal force was calculated the correlation was weaker (0.560). All the above research focuses on how force application changes to cause an increase in speed within an individual. The research does not approach how force application can be used to differ between different abilities and different magnitudes of maximum speeds.

The earliest research identified to investigate the internal kinetics of elite maximal sprinting was performed by Mann (1981) who used a sample of 15 athletes ranging from collegiate to world-class competitors. A combination of cameras and a force plate were used to investigate the net muscle moment patterns about the ankle, knee, hip and shoulder over the duration of a gait cycle. The inclusion of the kinetic data allowed the author to identify when flexor and extensor muscle moments were dominant throughout the ground and flight phases. The moments around the ankle were minimal during the flight phase but demonstrated plantar flexion dominance during the ground contact phase. At the knee there was extensor to flexor dominance during the flight phase, followed by flexor to extensor dominance during the ground contact phase. The hip moment demonstrated the opposite pattern with flexor to extensor dominance during the flight phase and extensor to flexor dominance during the ground contact phase. The highest values occurred during eccentric contraction, with the greatest muscle moment being exerted by the hip extensor/knee flexor muscle group during the initial point of ground contact (gluteus maximum and hamstrings). The relatively small muscle moments of the upper limbs suggest the arms simply have a role of maintaining balance. This was unique and novel research as it provided insight into how the kinematics of elite sprinting were being achieved.

The use of muscle moments can indicate which muscle groups dominate the activity, however exclusive muscle group activity cannot be ascertained. Whilst elite sprinters were included within the sample their results were not reported separately and therefore it is difficult to identify the kinetics that are associated with elite maximal sprinting. The author discusses that the largest deviation between sprinters occurred in the hip and knee moments around foot strike, and that better sprinters had larger hip extensor and knee flexor impulses. This subsequently minimised the horizontal braking force and led to a better maintenance of horizontal velocity. However the paper fails to report any of the GRF traces and therefore further discussions into the effect on minimising braking forces cannot be made. Vardaxis and Hoshizaki (1989) compared joint powers of the swing leg between intermediate (average horizontal velocity 9.11m/s) and advanced (average horizontal velocity 10.15m/s) sprinters over a 100m race. The camera was placed at 55m to get a profile of one stride at constant (maximal) velocity. As the focus of the research was solely on the swing leg an external force plate was not required, as segmental and joint powers were calculated from the video footage. They reported that whilst the profile of joint powers was the same between intermediate and advanced sprinters, the magnitude of joint powers (specifically hip and knee) were greater in advanced sprinters. The data indicated the hip joint was found to be the primary power generator, whilst the knee served to absorb and control the power generated from the hip. Bezodis et al. (2008)) reported that the hip extensors performed positive work in early stance, and the plantar flexors performed positive work in late stance. Vardaxis and Hoshizaki (1989) concluded the knee extensors played a negligible role during stance, and propose the knee is responsible for transfer of power from the hip through to the ankle rather than power generation itself.

Table 2-4 Summary table of research investigating the external kinetics of elite maximal velocity sprinting (>8.0m/s)

Study	Sample	Horizontal Velocity (m/s)	Ground contact time (s)	Max Fz (N)	Max Fz (BW)	Max Fy (N)	Braking phase duration (s)	Propulsive force duration (s)
Kyrolainen et al. (1999)	8 female and 9 male distance runners	9.00	0.115	2134		675	0.054	0.062
Weyand et al. (2000)	5 men	9.25			2.14			
Kuitunen et al (2002)	10 x male sprinters	9.73	0.094	2750				
Bezodis et al. (2007)	4 x male sprinters	9.80		2955	4.03		0.045	0.059
Bezodis et al. (2008)	1 x elite male sprinter	10.37	0.097	3240				
Morin et al. (2012)	1 elite male sprinter	8.66	0.121	1657	2.07	314		

Summary

Whilst the kinematic literature on maximal velocity running is extensive, the application of this research to elite athletes is limited due to inconsistency in running velocities studied. Research tends to be limited to slower speeds than would be evident in an elite population, which limits the application of findings to elite sprinters. In addition the available information on detailed kinematics of sprint technique is limited due to the difficulties of obtaining this information from high-end athletes. Furthermore the kinetic analyses of maximal sprint running are limited by methodology and the calibre of athletes tested. Subsequently the kinetic data on elite athletes is minimal and is associated with external validity limitations due to the method of data collection, which is often conducted on a treadmill or in a laboratory.

2.3 Theories of sprint running

A number of underlying sprint theories exist which have evolved as sprint performances have improved along with advancements in data collection technology. The theory trusted by a coach typically influences the training methods they adopt along with the critical determinants they believe to be relative to elite sprint performance.

As a pioneer in the research of sprint mechanics Ralph Mann aimed to investigate the relationship between performance variables and technique variables and collected a wealth of data from sprinters at varying speeds in order to identify which technique parameters are typical of elite sprint performance. He proposed the theory of ‘front side mechanics’ that movements behind the COM of the body should be minimised and instead athletes should focus on the movements of the leg forward of the COM. This then disputes the theory of ‘triple extension’ that is advocated in the current coaching literature. This is the notion that in order to increase stride length and to develop the maximum amount of force the athlete should reach full extension of the hip, knee and ankle joints at the point of TO. However this could be perceived as counterintuitive as it would increase the ground contact time (and subsequently decrease step frequency), and furthermore the effectiveness of force application in the latter stages of ground contact has been disputed. A limitation of this approach is that it is confined to biomechanical variables at key events in time, for example the touchdown and toe-off positions in maximal sprinting. It fails to take into account how these positions are reached, i.e. the joint angle and angular velocity profiles throughout the movement. This provides a more holistic analysis of the movement. Whilst examining individual joint kinematics has provided valuable understanding into sprint mechanics thus far, limited insight into joint interaction exists. Recently authors have acknowledged that the movement patterns in sprint running are determined by segment interactions (or joint couplings), yet a limited understanding of these couplings currently exists.

The earliest models of maximal velocity sprint running were derived from the deterministic models as pioneered by Hay (1993). A deterministic model provides a hierarchical illustration of how sprint variables (e.g. D_{TD}) influence a change in horizontal velocity (Figure 2-8). A limitation of a deterministic model is that the variables identified are performance variables and give no reference to the technique adopted to achieve them (Lees, 2002). The consideration of task outcome alone is an incomplete analysis of human movement (Heiderscheit, Hamill, & van Emmerik, 2002). For many complex skills performance is clearly related to aspects of technique that cannot be accounted for within a deterministic model of performance outcome. This is particularly relevant in sprinting as whilst the horizontal velocity is the product of step length and step frequency, it fails to identify how the technique (such as joint angles and angular velocities) impact on these performance variables. As technique parameters are not necessarily a mathematical quantity it cannot fit into the hierarchical process of a deterministic model and therefore a different approach must be taken. The statistical approach allows the strength between each of these technique related variables and the performance outcome to be established. The most commonly used statistical approach is multiple correlational analyses, however the use of this approach to investigate the relative importance of technique variables to performance is still rare within the literature. This approach has the advantage of a clear focus on technique rather than being clouded by the influence of performance variables (Lees, 2002).

The aim of this thesis is to develop a model of maximal velocity sprinting dictated by sound biomechanical principles. It is centred on the hierarchical model of sprinting, but progresses to establish how the general kinematic variables are influenced by technique variables, and secondly the role of the kinetics of maximal velocity sprinting.

As identified by Hay (1993) horizontal velocity is the product of stride length and stride frequency, or step length and step frequency. Stride length is the distance between successive points of initial contact of the same foot. Step length is the distance between the point of initial contact of one foot to the point of initial contact of the opposite foot. Step length is the sum of the distance travelled by the COM during stance (stance distance) and the distance travelled by the COM in flight (flight distance). Subsequently the stance distance is affected by the joint angles of the lower limbs (hip, knee and ankle) at both the point of TD and TO. Whilst it is perceived to be advantageous to maximise step length to increase velocity a consideration of biomechanical principles indicates this may not be the case. An increase in D_{TD} may lead to an increase in the braking forces at touchdown. The braking impulse at TD can be minimised by reducing the distance between the point of TD and the COM and increasing the foot speed at TD relative to the COM. Based on the impulse-momentum relationship a braking impulse will cause a decrease in horizontal velocity unless counteracted by an equal or greater propulsive impulse. Subsequently athletes may aim to increase the propulsive impulse by extending the time over which the propulsive force is applied. This is commonly achieved by maximising the extension of the lower limbs so the hip, knee and ankle joints reach full extension at the point of TO. Yet the effectiveness of force application at this latter stage of the stride has been questioned (Mann, 1985), and furthermore the increase in ground contact time to achieve this has a negative impact on step frequency.

In flight the COM acts as a projectile and therefore the flight distance is governed by the projectile motion equations and is dependent on the velocity and angle of the COM at TO and the relative height of the COM between TO and TD. The vertical height of the COM at TO and TD is dependent on the body position, in particular the degree of flexion at the hip, knee and ankle joints. The velocity and angle of COM at TO are a function of the resultant horizontal and vertical velocities of the COM at TO. At maximal velocity the change in horizontal velocity should be zero, and subsequently the horizontal force application should be minimised and confined to that necessary to overcome the braking forces. The force application at maximal velocity should predominantly be in the vertical direction. This allows enough vertical motion for the athlete to travel in flight necessary to reposition the limbs in time for the following ground contact. The flight time is important to velocity as it determines the step frequency.

Step frequency is defined as the number of strides per second and is a sum of the time spent in flight (swing time) and the time spent on the ground (GCT). The swing time refers not to the path of the COM as a projectile but to the movement of the segments around the COM during flight. The flight time can be minimised by increasing the velocity of the swing limb (by reducing the moment of inertia of the limb through flexion at the knee joint) and by reducing the distance through which the swing limb has to travel (by minimising triple extension at TO). Ground contact time is dependent on the distance travelled by the COM during ground contact (which as discussed earlier is the sum of TD and D_{TO}) and the velocity of the COM at TD. In running the whole body is commonly modelled as a body mass and a linear leg spring, and the vertical stiffness (defined as the ratio of the vertical leg spring at a given leg force during ground contact) is known to strongly influence running performance (Butler, Crowell, & Davis, 2003). The distance the COM travels during ground contact can be reduced by minimising the vertical oscillation of the COM during stance by increasing the stiffness of the hip, knee and ankle joints.

The studies later in this thesis will investigate these theories amongst elite athletes and develop a technical model of elite maximal velocity sprinting which incorporates both kinematic and kinetic aspects.

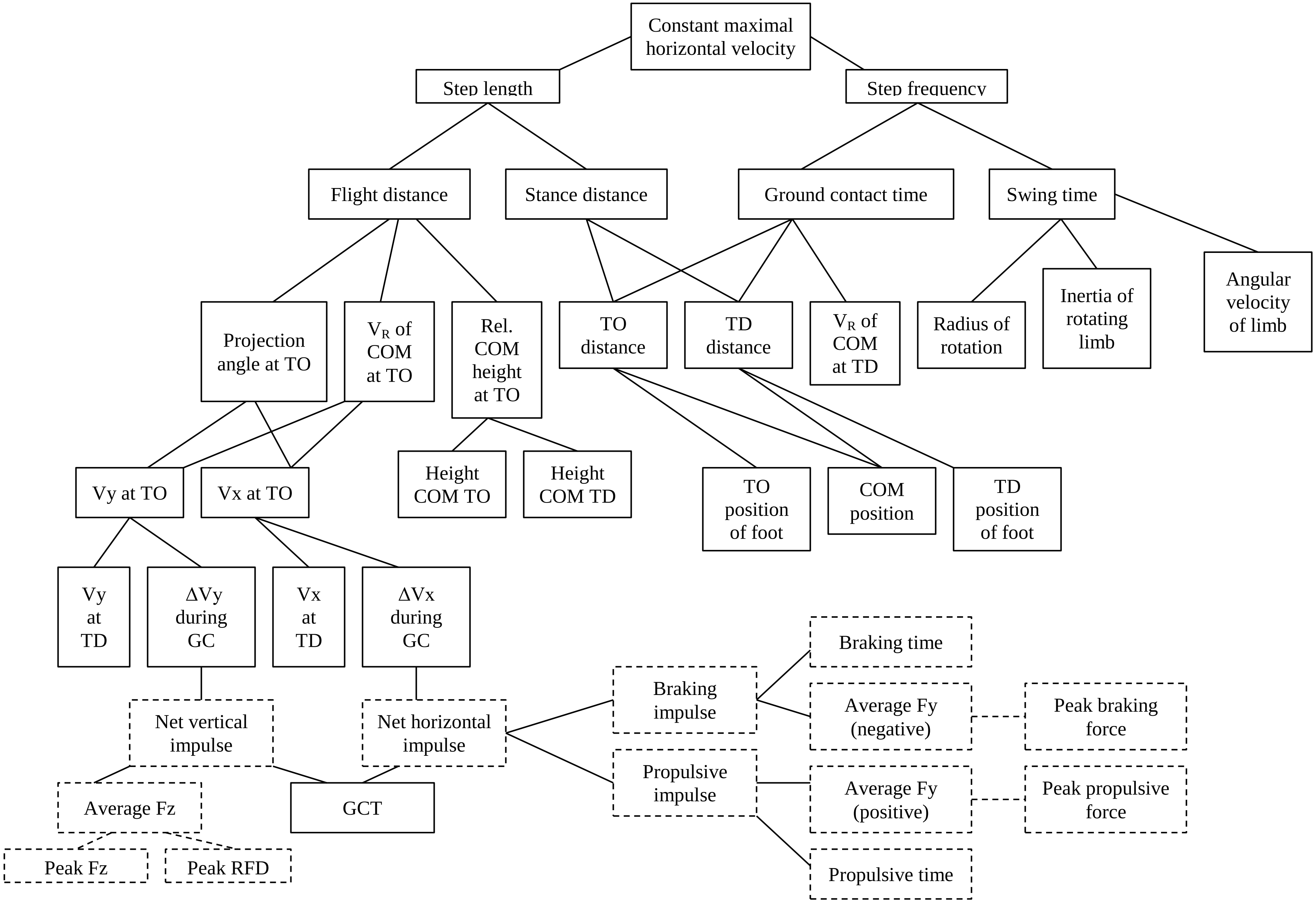


Figure 2-8 Deterministic model of maximal velocity sprinting. Kinematic variables (solid line boxes) and kinetic variables (broken line boxes).

2.4 Specificity of training

The training programmes of elite athletes are designed by coaches based on the six recognised principles of training (Table 2-5). The application of specificity to elite training programmes is becoming acknowledged as fundamental in shaping training responses (Kraemer, Ratamess, & French, 2002). Specificity of training can pertain to metabolic, psychological or biomechanical specificity. Gamble (2010) proposed that training specificity summarises two main concepts; firstly that the nature of the training response is dependent on the training stimulus, and secondly the degree to which training resembles the conditions faced during competition.

A term typically used by strength and conditioning coaches is the ‘SAID’ principle which stands for ‘Specific Adaptations to Imposed Demands’ (Baechle et al., 2000). The adaptations that occur in the various tissues and organs as a result of training are specific, in that adaptation only occurs in the muscles that have been stressed (Bosch & Klomp, 2005). Further, the manner under which the muscles undergo exertion determines the degree of specificity of the training load. The essence of training specificity is that the training responses elicited by a given exercise mode are directly related to the physiological elements involved in coping with the exercise stress (Kraemer et al., 2002).

The degree to which training resembles competition is described in terms of ‘transfer of training effect’ (Stone, Collins, Plisk, Haff, & Stone, 2000), which is determined by the level of bioenergetics and biomechanical specificity of training in relation to competition. By applying metabolic and mechanical specificity as the basis of training programmes it can positively influence transfer of training, and thus offer a means to improve the effectiveness and time-efficiency of an athlete’s preparation (Gamble, 2010). The authors also reported that as an athlete’s ability level improves, the level of specificity influences training responses to an increasing degree, and therefore specificity is particularly relevant to the training programmes of elite athletes. As a coach of elite sprinters Dan Pfaff adopts the term ‘minimum effective dose’ which is the notion of performing as minimal training as possible to gain the desired effects (D. Pfaff, personal communication, January 11, 2011). This is to maximise the recovery periods and to minimise the risk of injury from overtraining, and subsequently the training that is conducted must maximise efficiency and therefore specificity must be considered. Fry, Morton, Garcia-Webb, Crawford, and Keast (1992) showed that performance is enhanced if specificity of training is increased as competition phase approaches, therefore not only should coaches of elite athletes employ the principle of specificity into their training programmes, they should also take into consideration how this fits into the athletes yearly training plan.

Table 2-5 Definitions of the six training principles (taken from Campbell, Neil, and Winters-Stone (2012)

Principle	Description
Specificity	Training adaptations are specific to the system or muscles trained with exercise
Progression	Over time, the body adapts to exercise. For continued improvement, the volume or intensity must be increased
Overload	For an intervention to improve fitness it must be greater than what the individual is already doing
Initial values	Improvements in the outcome of interest will be greatest in those with lower initial values
Reversibility	Once a training stimulus is removed fitness levels will eventually return to baseline
Diminishing returns	The expected degree of improvement in fitness decreases as individuals become fit, thereby increasing the effort required for further improvements

The main focus of the current thesis relates to the concept of biomechanical specificity and how it can be implemented in the training programmes of elite athletes. The notion of biomechanical specificity is rare in peer-reviewed scientific journals; however it has received some attention in the coaching literature. Biomechanical specificity typically pertains to training reflecting the same movement patterns as the movement skill, and is assessed qualitatively on whether joints appear to operate through similar ranges of motion. However this definition gives no reference to the specificity of how these movement patterns are achieved, i.e. the kinetics of the skill being performed. The concept of biomechanical specificity must extend not only to replicating the movement pattern of the skills, but also to incorporate further kinematic and kinetic specific aspects. Both Gamble (2006) and

Graham-Smith et al. (2010) stressed that specificity of training should not be solely restricted to reflecting the movement patterns of the skill but should also incorporate the specificity of the velocity, loading, coordination and the balance of the skill itself. By focusing only on replicating the movement pattern the danger is that athletes train for their sport skill simply by performing the skill itself, which may result in overemphasis on a specific muscle group which could potentially lead to muscle imbalances and subsequently injury (Graham-Smith et al., 2010).

The appropriateness of training based on the biomechanical similarities to a target skill has been recognised as an important component in skill development in different sports. In swimming a common method of training is dry land training, often with the aim of replicating the swimming motion outside of the water against a resistance. Olbrecht and Clarys (1983) compared the EMG profile between front crawl simulation on dry land with an isokinetic bench in comparison to the EMG profile when swimming. Lower EMG activity of the deltoid muscles was higher on land than in water, despite the greater effort required in water to overcome the resistance. The authors concluded that specific training cannot be accomplished with dry land devices due to both mechanical and environmental differences. An additional technique used in swimming is the use of hand paddles, however it is necessary to establish whether the use of hand paddles subsequently changes the kinematics of the stroke, and thus compromising their biomechanical specificity. Gourgoulis, Aggeloussis, Vezos, and Mavromatis (2006) investigated the changes in freestyle stroke kinematics (at constant stroke rate) with hand paddles of two different sizes. The use of hand paddles significantly increased swim velocity and stroke length but did not significantly alter stroke kinematics. Thus it was concluded hand paddles could be an appropriate training tool for improving swimming freestyle performance. Rowers often perform dry land training with the use of an ergometer. Elliott, Lyttle, and Birkett (2002) compared both stroke and body position kinematics between ergometer rowing and on-water rowing in a sample of eight national-level rowers. Stroke angle and length were similar for both types of rowing, and the force curves were highly correlated between ergometer and on-water rowing. The body positions at the catch and the finish of the stroke were similar between the ergometer and on-water rowing across all stroke rates. The results indicate that the technique utilised by the athletes on the ergometer closely replicates that of on-water training, thus validating its use as a training tool. In gymnastics the performance of complex skills requires coaches to develop training methods to practice the skills in a safe and effective manner. Skill progressions form the main focus of gymnastic training and coaches use the concept of specificity to encourage performance-related adaptations. The importance of biomechanical specificity between progressions and the target skill was emphasised by Kolar, Kolar, and Stuhec (2002) who suggested that progressions should be based on educational principles and should mimic the movement pattern of the target skill. Thus Irwin and Kerwin (2005) aimed to quantify the biomechanical similarity between the progressions of training for the longswing in gymnastics. The authors used a ranking system based on the similarity of the progression to the skill based on various body position kinematics. This provides coaches with a method to select training skills based on their biomechanical similarity to a skill.

Due to the high impact nature of the triple jump, training drills are used to practice the skill at a lower intensity. Wilson, Simpson, and Hamill (2009) endeavoured to determine the effectiveness of training drills in replicating the lower extremity coordination patterns used during the triple jump. This study was the first to use elite level athletes as their subjects, which increases the comparability of the results to elite level sprinters. Five elite triple jumpers (defined as a personal best >70% of the world record) performed four typical plyometric drills along with a complete triple jump. The coordination strategies represented as joint-couplings were compared between the five conditions. The use of interjoint coordination provides a more holistic view on which to analyse the movement and describes how the joints are moving in relation to each other, which is particularly important in cyclical movements such as the triple jump and sprinting. The authors used continuous relative phase to quantify the interjoint coordination and the associated variability. Differences were observed in the coordination patterns between the triple jump and static drills, but not between the triple jump and the dynamic drills, with the differences occurring predominantly in the free leg as opposed to the stance leg. The authors conclude that if the primary purpose of the drill is to replicate the movement patterns then dynamic drills are more appropriate. In addition the considerable differences shown in the free leg stresses the same issue as identified by Grimshaw, Marar, Salo, Knight, and Vernon (1995), that it is important when performing single leg drills that the opposite leg is controlled and remains specific to the full skill.

So whilst the biomechanical specificity of training methods has been explored in a number of sports there is limited research with respect to sprinting. Although various sprint-training methods appear to exploit the concept of biomechanical specificity (e.g. running drills/resisted training) their level of specificity is yet to be quantified. Similarly the importance of specificity in strength and conditioning is well recognised, but the specificity of such exercises to maximal sprinting is yet to be established.

2.5 Specificity of sprint training methods

2.5.1 Introduction

As with any sport to achieve the highest levels of performance an athlete must train for their event over a number of years. Effective coaching involves developing the proper balance of biomechanics, physiology, and psychology to improve human performance. In order to achieve an optimal balance of the above factors, precise training methods are needed. This training is usually dictated by a coach and is based on individual knowledge and experience; however a coach may also draw on scientific research to dictate their training plans.

2.5.2 Training drills

The use of running drills in sprint training is widespread, however the variance in type and technical execution of these drills is vast. Running drills are utilised to develop the optimal movement and coordination patterns of sprinting (Harrison, 2010), however scientific research is yet to establish whether running drills achieve this desired component. Subsequently the support for running drills is based mainly on anecdotal evidence from coaches e.g. Dick (1989) and Korchemny (1994) rather than sound scientific evidence.

The rationale for the use of running drills is based on the concept of skill acquisition and kinesthesis. By reaching the autonomous phase of a skill an athlete can perform a skill automatically without conscious thought. Reaching this final stage of learning is only realised after much practice, quality repetition and experience with the specific task (Morley, 2005). This is dependent on the athlete developing a motor programme by which the movements are stored in the athlete's long-term memory. The motor programme is called upon when the action is so fast (as with sprinting), such that the athlete has no time to act on any feedback. The theory of practice specificity suggests that maximal retention of a task is facilitated by practice conditions that mimic the task conditions (Henry, 1968), and which therefore maximise external validity. Subsequently training practices and drills should resemble the movement patterns of the skill (Lauder & Payton, 1995). Drills and other forms of deliberate practice involving repetition and successful refinement are known to be strongly associated with athletic performance (Ericsson, Krampe, & Tesch-Römer, 1993). The majority of current methods for technique correction and skill development across all sports rely on some form of drill e.g. Larkins (1987).

Although not based on scientific research and not presented in peer reviewed journals running drills have received a lot of attention within the sprint coaching literature. Bell (1995) proposes that a movement done numerous times (as with a drill) will lead to more efficient neuromuscular patterns, which will in turn lead to better and more consistent performances. Subsequently the training load can be increased without additional stress to the athlete. As head track coach at Indiana University, Sam Bell uses drills to lead to a more efficient stride pattern and create a movement that allows for a faster cadence (or stride frequency), which leads to the development of running patterns to create speed. As national hurdles coach of Canada, Brett McFarlane identifies that sprinting is a series of finely tuned technical and motor coordinated skills that must be rehearsed at high speeds to reinforce the correct patterns (McFarlane, 1994). The role of specific drills is therefore to isolate and combine joints to rehearse a series of sensations that establish exact motor pathways. McFarlane (1994) distinguishes between drills of the 'basic technical model' which have a high degree of specificity and meet the motor unit demands, to the drills of an 'advanced technical model' which involves conducting the drills at high speed to focus on firing motor units at the highest velocities possible. Jarver (1978) identified that sprint performance is dependent on the ability to improve the functioning of the nervous system and the coordination of the muscles used to produce a movement pattern, the ability of which directly affects technique. In addition Dare (1994) suggest a further benefit of drills is to specifically strengthen the muscles in postures and actions that are similar to those that occur in the sprint action.

Due to the strong association between practice and performance it is important the drills employed are relative to the skill being improved. Harrison and Warden (2003) proposed that running drills should be more correctly termed 'rehearsal drills' as they should be used to rehearse some aspect of the running skill itself. Drills are employed as the 'part' of the 'whole-part-whole' training method and subsequently are often termed 'isolation drills'. Part practice is used for complex skills and breaks the skill down into its sub-routines and then each part is practiced separately before being included into the whole skill again. This is particularly beneficial for movements when the full skill places high loads on the body (e.g. the triple jump) and therefore repetitions of the full movement should be limited.

In contrast sprinting is a cyclical action, and therefore breaking the skill down into its respective parts may interrupt the existing motor program, and thus for the 'whole-part-whole' approach to be successful the drills must relate well to the technique and activate the muscles in patterns that are consistent with sprinting. Closer inspection of some drills has revealed they have questionable relevance to sprinting. Mann (1986) discussed briefly the inappropriate use of bounding drills for sprinting. He identified that in bounding drills the ground contact time (0.300s) is three times longer than when sprinting (0.100s), which is the opposite of what the athlete should be focusing on. Thus he proposes that coaches use drills that simulate the explosive sprinting action, specifically bounding drills which produce vertical velocity without deep flexion at the knees. However Mann (1986) fails to acknowledge the potential benefits of the progressive overload of tolerating higher landing forces. By extending the ground contact time the limbs are moving slower, and at slower speeds the limbs are able to produce more force (force-velocity relationship of muscle). Harrison and Warden (2003) investigated the heel flick drill, which is assumed to mimic the knee flexion action during the early swing phase of sprinting. However they reported that the heel flick is not consistent with the pattern of movement in sprinting, as in sprinting knee flexion occurs simultaneously with hip flexion, or even slightly after hip flexion, whereas in the heel flick drill knee flexion occurs in isolation. The knee flexion in the heel flick is initiated by contraction of the hamstrings, however EMG studies have identified that the hamstrings are not active immediately after toe-off (Chumanov, Heiderscheit, & Thelen, 2007), and therefore the heel flick drills lack biomechanical specificity with respect to the muscle groups recruited.

Following a review of the coaching literature it becomes evident that a number of drills are repeatedly implemented across training programmes. The recognised pioneer in the development of running drills was Gerard Mach. Mach was a successful sprinter who progressed to becoming the Polish national track and field coach. Mach then emigrated to Canada and took across his concept of running drills, and became the national sprint and hurdle coach of the Canadian team in 1973 and was appointed Head Coach of the national team in 1976. Mach ensured specificity of the drills by relating them to some aspect of the stride component; the knee lift, foreleg action and push-off. The drills were termed 'A', 'B' and 'C' drills dependent on which aspect of the stride component they focused on respectively.

The focus of the 'A' drill is the knee lift, which is important in running. The legs alternate with one leg supporting and the opposite leg driving to a position of hip flexion (bringing the thigh to the horizontal) with the knee flexed. In this position the ankle should be dorsiflexed. The hip and knee then rapidly extend simultaneously towards the ground, with the ankle remaining in a dorsiflexed position. The phases alternate between the legs. The mechanics of the upper body should resemble the sprinting action with a slight forward lean. The arms should exhibit a vigorous arm action in order the balance the leg action. The 'skip' action requires that the knee lift in the swing leg occurs over the period of two ground contacts of the stance leg.

Figure 2-9 Diagrammatic example of the 'A skip' (Kivi, 1997)

The mechanics of the ‘B’ drill are similar to the ‘A’ drill except from the path of the leg in swing. The focus of the ‘B’ drill is the foreleg reach. Here instead of hip and knee extension occurring simultaneously to bring the foot underneath the body, the initial action is the extension of the knee, followed by driving the foot down using the hip extensors. The resulting path of the foot is in a circular position from the front of the body to contacting underneath the body. Ground contact occurs slightly in front of the centre of mass (as with sprinting). The ‘B’ drill is often termed the ‘pawing’ drill in the literature due to the downwards and backwards motion of the foot which is likened to ‘pawing’ against the ground. This backwards movement of the foot relative to the forward motion of the body is a critical feature of sprinting as it reduces the D_{TD} and braking forces which reduce horizontal velocity.

Figure 2-10 Diagrammatic example of the 'B skip' (Kivi, 1997)

Whilst the description of the drills has been discussed it is also important to consider the execution of drills; namely the intensity, duration and frequency at which they are performed. Mach suggests that drills should progress from a walking to a skipping to a running action as the athlete becomes proficient in performing them. At walking pace one foot will always be in contact with the ground, whilst at skipping pace the stance leg performs a skipping action whilst the opposing leg is passing through the swing phase. Once the running stage is reached the drills are performed at a running pace and the ground contacts alternate between each leg. The use of speed progression in drills was also advocated by McFarlane (1994). Mach emphasises that drills should be executed at approximately '3 steps per metre'. The drills are usually performed at the beginning of the training session, with each drill performed over 30-40m, progressing from walking through to running. Occasionally the drill is then linked to acceleration, in which the drill leads straight into an acceleration phase. For example the drill would be performed over 10 metres and then the athletes accelerates for the subsequent 30 metres. The goal of this is to take the 'part' of the skill and incorporate it immediately into the 'whole' skill, as stressed by McNab (2006). With regards to frequency it is recommended drills become part of the daily preparation of the athlete and are performed at the start of every training session, consequently for elite athletes this may mean performing the drills 5-6 times per week. However at such frequency it is important the drills are executed correctly, as incorrect execution could become engrained and actually be detrimental to technique (Gambetta, 1991). For example a common error is for athletes to lean backwards when performing the high knee drills, whereas in sprinting the body should have a slight forward lean. By leaning back during the drills it is possible this upper body position would translate into their running which would be detrimental to performance. An important point raised by Harrison (2010) is that drills should be selected for each athlete to improve specific aspects of technique or to correct faults to avoid each athlete performing all drills possible. Morley (2005) also supported this point by stating that if a drill is to be used, a coach should sort out a drill appropriate to the level of proficiency of the athlete, not the "one drill for all" routine which is very negative, particularly to the elite athlete.

Harrison (2010) stressed the importance that coaches must understand whether drills are producing the desired effect. So whilst it is recognised that drills should reflect some part of the running action and should be performed correctly to reap the benefits, little research has actually been conducted as to whether the drills mentioned above accurately replicate elite sprinting technique. To the authors knowledge only one paper has addressed this topic. An MSc thesis by Kivi (1997) researched the kinematic comparison between two commonly employed running drills (‘A’ and ‘B’) to sprinting. Using a sample of 8 university athletes (100m PB 10.62-12.10s) they each performed three repetitions of both the ‘A’ and ‘B’ drill as detailed earlier. They then performed two 60m maximal velocity runs to facilitate comparisons to maximal sprinting. Video cameras recorded selected kinematics for both the drills and the sprinting. Neither horizontal velocity nor 60m-time are reported by the author and therefore the previously defined method to classify ‘elite’ cannot be employed. Moreover stride length is not reported and therefore horizontal velocity cannot be derived from the product of stride length and stride frequency.

A one-way ANOVA was used to identify significant differences between ‘A’ drill and ‘B’ drill, between ‘A’ drill and sprinting, and between ‘B’ drill and sprinting. There were no significant differences between ‘A’ and ‘B’ drill and therefore their results were combined for subsequent comparison with maximal sprinting. There were a number of significant differences between the drills and sprinting. The general kinematic variables that were significantly different were stride frequency (and therefore ground contact and flight time), vertical displacement of the COM and vertical velocity of the COM. Significant differences in joint angles were seen for shoulder and ankle ROM, trunk flexion and rotation, pelvic rotation and hip flexion. Further when angular velocities were investigated there were significant differences for hip and knee extension angular velocity, ankle dorsi and plantar flexion velocity and elbow flexion angular velocity. Furthermore differences were seen in the timing of peak angular velocities and the angles at which peak velocity occurred for the shoulder and ankle. From this it was concluded the kinematics of ‘A’ and ‘B’ drills differ noticeably to sprinting and therefore their use in training should be reconsidered. However the author failed to define beforehand which kinematic variables should be specific based on the purpose of the drills and subsequently just reported all variables available. Targeting the research based on a predefined technical model of sprinting would enable the research to focus on critical elements to sprinting. The applicability of this research to an elite training population is limited due to the difference in skill level of the athletes which not only limited the maximal velocity of the sprinting trials but also potentially the execution of the drills.

Whilst not in sprinting, similar research by Grimshaw et al. (1995) aimed to establish the kinematic characteristics of the lead and trail leg in hurdle drills and whether these were comparable to full hurdle clearances. Although junior athletes were used for this research it was deemed acceptable for inclusion in the literature review as the main aim of the research was to compare drills with the hurdling action. Five junior athletes performed a lead leg and trail leg isolation drill followed by a full hurdle clearance, from which video was digitised using a 14-segment model. Unsurprisingly the drills were performed at a slower horizontal velocity (5.87 and 5.67m/s for the lead and trail leg drills respectively) than the full hurdle clearance (7.09m/s). This was attributed to the difference in the stride pattern used in drills compared to a full clearance. A technical model of hurdling has identified a critical factor in hurdling is the takeoff distance before the hurdle and the landing distance off the hurdle, and their relative percentage contributions to overall clearance distance. The overall clearance distance for the full hurdle clearance was 3.47m, whereas for the lead and trail leg drills it was 2.74m and 2.60m respectively. Whilst this would be expected due to the differences in horizontal velocity the relative contributions between takeoff and landing also vary, suggesting there are differing characteristics between hurdling and the drills. In a full clearance the percentage contribution to overall distance is 57% for takeoff and 43% for landing distance respectively. However for the lead leg drill there was more contribution from the takeoff leg, and for the trail leg drill there was contribution from the landing leg. This becomes relevant when it comes to transferring the drills to full hurdling. It is probable that in the drills the athlete is only focusing on a single limb (either lead or trail) and not focusing on the mechanics of the opposite leg (and subsequently takeoff and landing distances are varying). Whilst this is acceptable in the drills as the opposite leg does not have to clear a hurdle, if transferred to full hurdling action is it possible this opposite leg action would collide with the hurdle. It can be argued that if the focus of the drill is the lead leg then the actions of the trail leg are irrelevant, however the more the drill is removed from the actual skill the more its relevance must be questioned. The hip, knee and ankle angles for both the lead and trail legs were compared between sprinting and each of the drills. Due to their irrelevance to the rest of the thesis the actual angles will not be discussed here, however it was noted there were considerable differences in angles between sprinting and the hurdling drills. The authors concluded there are considerable variations between the drills and full hurdling, though accept that a number of these differences can be attributed to the differences in speed at which the drills are performed. It seemed evident that athletes tended to perform the drills in the 'easiest' manner rather than performing the drills in the context of the full clearance. Therefore this is support for the notion that if drills are to be included as part of a training session it is important they are conducted correctly and in a manner that reflects the whole skill, otherwise the transference of technique and motor patterns will be limited.

In summary the use of isolation drills for sprint training is widespread, yet the scientific evidence behind these as an appropriate training drill to improve sprinting is limited, especially among elite athletes.

2.5.3 Strength training

In order to accelerate to and maintain maximum velocity it is crucial to have speed, strength or power, where power is the product of speed (velocity) and strength (force) (Tricoli, Lamas, Carnevale, & Ugrinowitsch, 2005). It is generally accepted that sprint speed can be improved considerably by strength training, and subsequently strength and conditioning programmes form a substantial part of sprinters training (Zatsiorsky & Kraemer, 1995). The role of the lower limb musculature in generating power and achieving maximal velocity provides a sound rationale for improving the strength and power of these muscles. Force production in maximal velocity sprinting requires the contraction of several muscles or muscle groups across multiple joints. Previously it was believed that increases in strength following a strength training programme were exclusively the result of hypertrophy (Bosch & Klomp, 2005). However research by Wilmore and Costill (1994) showed that following a 6-week training programme the higher levels of strength attained could not be attributed solely to hypertrophy. This research supports the conclusion there must be other processes responsible for increasing strength. Therefore strength training for sprinting must aim for not only selective hypertrophy of fast twitch fibres but also specific adaptations of the nervous system (Delecluse, 1997). The deterministic model of sprinting (Figure 2-2) indicated that ground contact time is a critical determinant of horizontal velocity. Furthermore the model reveals that average force (and the time over which it is applied) is a determinant of step length. When traveling at maximal velocity an athlete is on contact with the ground for approximately 0.100s, and therefore the ability to apply force over a short period time is a critical component of elite maximal velocity sprinting. Subsequently a strength-training programme should also focus on the improvement of rate of force development so a sprinter can reach their maximum force during a short ground contact.

Strength training is typically divided into three categories which is dependent on where the action of the muscle fibre lies on the force-velocity continuum (Figure 2-11). Maximum strength refers to exercises which are executed as forcefully as possible without causing a shortening muscle contraction whilst exercises that are performed rapidly fall in the category of fast-power training. Similarly there are categories that are not based on the force-velocity relationship such as strength endurance and hypertrophy training. However as functional movement is only slightly related to the force-velocity continuum it is necessary to formulate other reasons for integrating a certain type of strength training into a training programme (Bosch & Klomp, 2005). Subsequently strength training for sprinting must be viewed multi-dimensionally and is not limited to just developing a sprinters maximal strength. Rutherford and Jones (1986) emphasise such strength and conditioning programmes should be an individualised and an event specific process. Maximal velocity is directly related to the velocity of the swing back of the legs, starting from the high point of the knee lift to foot contact and continued throughout the support phase (Wiemann & Tidow, 1995). Subsequently maximal velocity sprinting is predominantly determined by the action of the hamstrings, gluteus maximus and adductor magnus.

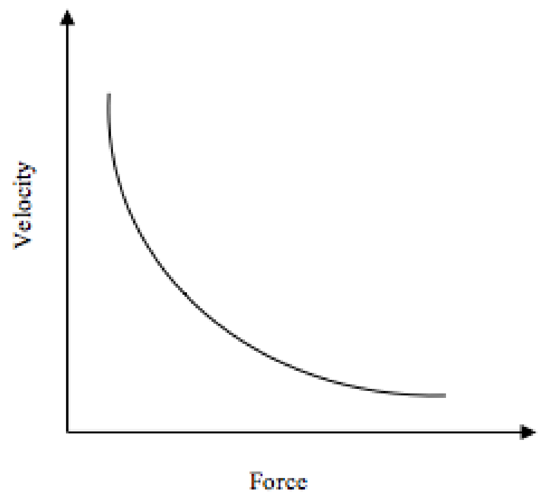


Figure 2-11 Force-velocity continuum

A review of the influence of strength training on sprint running performance is provided by Delecluse (1997). However the focus of this review will be the application of the principle of specificity to strength and conditioning programmes. It has been recognised in order to maximise the transference to sprinting the strength training should be specific to the sprinting action. Strength training programmes are perhaps the component of sprint training that have embraced the concept of biomechanical specificity most readily, although this is often confined solely to movement pattern specificity. As aforementioned Gamble (2006) and Graham-Smith et al. (2010) stressed that specificity of training should not be solely restricted to reflecting the movement patterns of the skill, but should also incorporate the specificity of the coordination, speed, loading and balance principles of the skill itself (Figure 2-12).

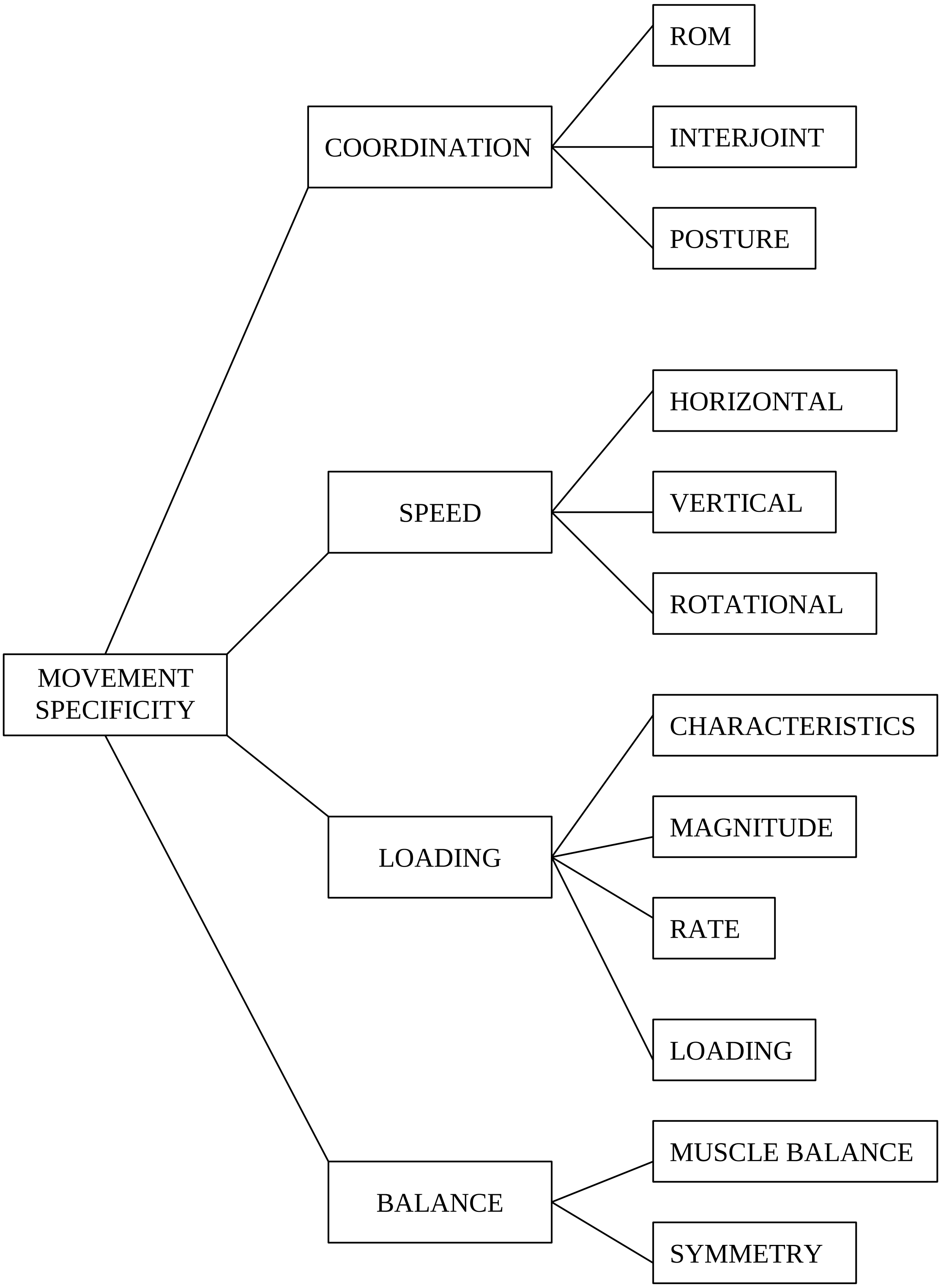


Figure 2-12 Movement specificity principles (Graham-Smith, Comfort, Jones, & Matthews, 2010)

Coordination principles

The strive to achieve movement coordination specificity is often limited to a coach selecting exercises that seem to occur through similar ranges of motion to the skill in question. In a velocity specificity research study Blazevich and Jenkins (2002) endeavoured to select strength exercises that mimicked the sprint action, for example the unilateral hip extension and flexion exercises in which force was applied through the ranges of motion typical of upright sprint running. The authors proposed that velocity-specific effects were more pronounced when the movement patterns of the strength training exercises matched those of the sprinting.

The movement coordination profile and associated ROM of a skill have an impact on the force-length relationship of the muscle. This relates to the amount of overlap between actin and myosin filaments and the extent to which they can slide across each other which affects the amount of force the muscle can produce. The coordination profile can either relate to the angle at which an isometric lift is performed at, or it can refer to the range of motion over a concentric and/or eccentric contraction.

Early research has shown that isometric strength training effects are specific to the joint angle selected for training, and that specificity is more marked when training has occurred at a joint angle that places muscles at a relatively short muscle length (Thepaut-Mathieu, Van Hoecke, & Maton, 1988). Angular specificity is proposed to be a result of neural adaptation, as it has been argued that a muscular adaptation (such as hypertrophy) would improve strength across all muscle lengths (i.e. all joint angles) (Sale & Macdougall, 1981). Thepaut-Mathieu et al. (1988) provided evidence of neural adaptation from their research as there was a greater motor unit activation at the joint angles trained.

Kitai and Sale (1989) aimed to identify the mechanism behind joint angle specificity in isometric training by studying the effects of isometric training at one joint angle on both voluntary and evoked contraction strength across a range of joint angles. Six healthy women underwent a 6-week isometric training programme of the left plantarflexors of the ankle joint at an angle of 90°. Voluntary and evoked isometric contraction strength was measured at the training angle and at 5, 10, 15, 20 and 25° intervals in the plantar and dorsi flexion directions. Training increased voluntary strength at the training angle and two adjacent angles only, confirming the existence of joint angle specificity in isometric training. Further, evoked twitch torque did not increase significantly at any angle, thus it was concluded that a neural mechanism is responsible for the joint angle specific increase as opposed to a muscular adaptation. Knapik, Mawdsley, and Ramos (1983) investigated the angular specificity of isometric training of the elbow angle and reported strength gains within 20° of the training angle. In a practical sense this means that the benefits of training at one joint angle could transfer to a range within 20° of the training angle.

A more advanced theory related to the concept of coordination specificity in strength training is the specificity of interjoint coordination. Typically sports actions, and in particular sprinting, are a highly coordinated action between various joints and muscles. Thus the isolated training of singular joints (as often adopted in research studies) is not applicable to the typical training programmes of elite athletes. Leirdal, Roeleveld, and Ettema (2008) proposed that training a combined movement of knee extension and ankle plantarflexion would be more effective at improving vertical jump performance than training each of these movements in isolation. In a vertical jump the joint movements occur in a proximal-distance sequence starting with hip extension, followed by knee extension and then powerful plantarflexion. Ankle power in a vertical jump has been shown to range between 2000-4000W, however if this plantarflexion were to be performed in isolation the power is limited to 200W (Bobbert & van Ingen Schenau, 1990). The magnitude of such difference can be attributed to the role of biarticular muscles in vertical jumping which are not activated when plantarflexion occurs in isolation. Thus the aim of the research by Leirdal et al. (2008) was to compare two different training methods with and without the possibility to exploit the biarticular aspect of the gastrocnemius muscle. Twenty athletes were assigned to groups based on their vertical jump performance. One group trained squats and plantar flexion separately (single group), whilst the other group performed squats with the plantarflexion incorporated at the end of the movement (multi group). Both groups lifted 40% of their individual isometric force and were instructed to perform the lifts as fast and explosively as possible. Both groups increased their peak power, however there were no significant differences between groups, and neither group significantly improved vertical jump performance. However the data did indicate different coordinative changes in the vertical jump between the two groups, which is in line with simulation studies that have shown that an increase in strength of the leg extensor muscles requires an alteration in the muscle activity pattern in order to improve jump performance (Nagano & Gerritsen, 2001). The multi group shifted the proximal-distal sequence towards hip extension and a more tightly coupled knee extension and plantarflexion, whereas the single group shifted towards a more tightly coupled hip and knee extension, followed by a more isolated plantarflexion. These opposite observed effects indicate the movement specificity principle in training. Thus it was proposed that the shift in the coordination pattern between the two groups might be the forerunner to improvements in vertical jumping. This finding raises the question about how specific a training movement must be before the effects on coordinative aspects can be transferred to the actual sports skill, which is the overall goal of a strength and conditioning coach.

Wilson, Murphy, and Walshe (1996) explored this theory by investigating the importance of performing strength training exercises in postures specific to the movements they are attempting to facilitate. A group of 27 subjects underwent an 8-week training programme of the squat and bench press lifts. The effect of the strength programme on maximal bench press and squat strength was assessed, along with sports specific movements of bench press throw, vertical jump, push-up, 40m-sprint, 6s-cycle and various isokinetic tests. The results supported the concept that posture is important in training as those exercises conducted in similar postures to the training recorded the greatest improvement in performance. The authors propose that the mechanism of posture specificity may be related to the effect of posture on neural input to the musculature, and therefore stress the importance of selecting strength training exercises which reflect the posture of the sport specific movements.

Speed principles

Velocity specificity is important as the speed of the movement has an important function on the levels of loading, the ability to generate force and typical movement or ground contact times (Graham-Smith et al., 2010). The nature of velocity specificity is that strength gains tend to be restricted to the velocities at which the muscles are trained, which is more pronounced at the higher end of the velocity spectrum (Morrissey, Harman, & Johnson, 1995). At lower velocities strength gains may be evident below the training velocity, yet when operating in the upper region of the force-velocity curve improvements are only registered within the narrow range of velocities used in training. However strength coaches often misunderstand the concept of velocity specificity, particularly when designing training programmes for sprinters. Movement structures in sprinting and plyometric exercises are very similar in relation to muscle contractions, along with external movement structure and time of execution (Coh & Mackala, 2013). The intention of replicating the sprint action often means strength coaches prescribe plyometric exercises (e.g. drop jumps) to replicate the ground contact times in sprinting, which are typically 0.100 seconds. However to try and replicate such contact times during plyometric exercises is impractical without a change in mechanics due to the notion that drop jumps have little or no horizontal movement. Subsequently strength and conditioning coaches must understand the relationships between speed, contact times and technique before prescribing exercises – and take into account all elements of biomechanical specificity.

Coyle et al. (1981) investigated whether performance improvements in peak torque were specific to the velocity of a 6-week knee extension training programme, and what were the potential mechanisms for any observed improvements. College aged males were split into three groups; slow velocity training (60°/s), fast velocity training (300°/s) or mixed velocity training (60°/s and 300°/s). The slow velocity group only saw significant improvements in peak torque at their training velocity, whereas the mixed training group saw significant improvements at both 60°/s and 300°/s, but not at the mid-velocity of 180°/s. The training specificity observed by these two groups suggests that neural mechanisms were responsible for the increase in peak torque as the muscle morphology (by means of muscle biopsy) remained unchanged. However the fast velocity training group demonstrated a significant enlargement of Type II fibres and saw both improvements at their training velocity and at the mid-velocity. These data suggest muscle hypertrophy was the mechanism responsible for training improvements in the fast velocity group rather than a neural mechanism. Whilst highlighting that slow velocity training does not improve torque at faster velocities, the finding that fast velocity training is transferrable to slower velocities may have some practical applications when designing training programmes. A limitation of such research is the velocities are restricted by an isokinetic dynamometer. Specifically Mann (2010) documents typical limb speeds during elite sprinting and reports limb speeds in excess of 400°/s for the upper leg during ground contact and recovery and a lower limb speed of 350°/s at touchdown, and therefore the study of high-velocity training is perhaps more relevant to elite athletes than slow velocity training.

Whilst the advantage of utilising an isokinetic dynamometer for the training programme is that speed of movement can be controlled, it is rarely used as a training tool by elite athletes due to the lack of its specificity to the rest of the sprinting action. Actual sport movements typically involve acceleration and deceleration rather than a controlled constant velocity, and therefore practical results from isokinetic research are limited. Cormie, McGuigan, and Newton (2010) compared the effectiveness of heavy strength training versus ballistic power training in a sample of weak men. The strength group performed back squats at 75-90% of their 1RM whilst the power group performed jump squats with 0-30% of their 1RM over a period of 10 weeks with 3 sessions per week. Both groups improved both jump and sprint performance following the 10-week training period with no significant difference between groups. However the strength group saw a 31.2% improvement in maximal strength whilst the power group only achieved a 4.5% improvement. Performance improvements were mediated through neuromuscular adaptations specific to the training stimulus, thus it was concluded the strength training was more effective for weak individuals. However it is proposed that the relationships may vary for well-trained individuals.

McBride, Triplett-McBride, Davie, and Newton (2002) investigated the improvement in sprint times following an 8-week training program in 26 athletic men when assigned either a training program with heavy squats (80% 1RM) or light load jump squats (30% 1RM). The group who trained with light load squats saw a significant improvement in sprint time in comparison to the heavy-load group. The authors concluded that training with light load jump squats resulted in increased movement velocity capabilities and that velocity specific changes in muscle activity may play a key role in this adaptation. Yet the limited duration of the training programmes characteristically used in research limits the applicability of these findings to elite athletes undergoing year-round strength-training programmes.

A conflicting hypothesis to the current mechanisms for the velocity-specific response to strength training is that it is the intention to move explosively which is more important then the actual velocity achieved during the movement (Behm & Sale, 1993). Conscious effort to exert maximal force has been found to significantly influence gains in strength and power (Jones et al. 1999). The intent to move explosively is integral to the neural mechanisms associated with adaptions in high-velocity strength and rate of force development (Ives & Shelley, 2003). Further the recruitment and firing of muscles during training have been shown to be part dictated by what is anticipated prior to the movement (Behm & Sale, 1993). This could have potential implications to the design of training programmes as the intent to move explosively could be favoured over high-velocity training due to the potential reduction in injury risk.

Behm and Sale (1993) were the pioneers of this concept and investigated its application over a 16-week training programme. Eight men and eight women conducted unilateral ankle dorsiflexions against resistance that either resulted in an isometric contraction (one limb), or an isotonic contraction at high-velocity (300°/s) (opposite limb). However both groups were instructed to intend to move the load explosively. Training produced the same high velocity-specific training response in both limbs, with peak torque increased most at 300°/s (38%) in comparison to slower velocities, thus indicating evidence of training velocity specificity. This percentage improvement is greater than those reported in previously mentioned studies, however this may be attributed to the fact the training programme adopted by Behm and Sale (1993) was a 16-week programme which is longer than the programmes previously discussed. The training responses still occurred even when the device restricted the rapid movement. This suggests that the principal stimuli for the velocity specific response is the high rate of force development of the ensuing contraction as opposed to the type of muscle contraction (isometric or concentric). A summary of the potential mechanisms for velocity specific training in the diagram by Kawamori and Newton (2006) below.

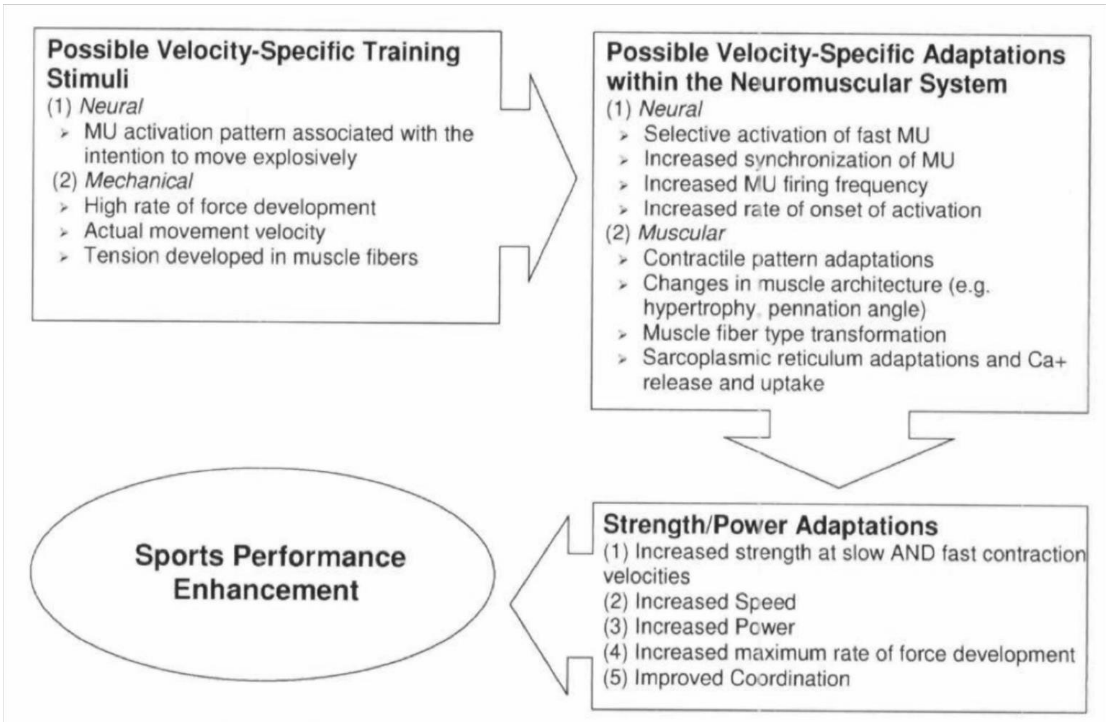


Figure 2-13 Potential mechanisms of velocity specificity (MU = motor units) (Kawamori & Newton, 2006)

Loading principles

When selecting exercises for a strength programme a coach must have an understanding of the characteristics of the force loading, the magnitude and the rate of the loading. The characteristics of the force loading is determined somewhat by the training mode employed: isometric, isokinetic or isotonic. It has been shown isometric training results in large and rapid increases in strength in a relatively short period of time (Thepaut-Mathieu et al., 1988). However a limitation of isometric training is that it produces highly length-specific adaptations with little transfer to other muscle lengths (Kitai & Sale, 1989). In contrast dynamic strength training results in smaller strength increases but across the full range of the training movement (Graves, Pollock, Jones, Colvin, & Leggett, 1989). Folland, Hawker, Leach, Little, and Jones (2005) investigated the specificity of isometric vs. isokinetic contractions. The sample was divided into a group that trained isometrically (at 90°), and a group which trained isokinetically at 30°/s. This is much slower than the speeds reported in the previous research investigating the effect of velocity specificity on strength improvements, low velocity groups were typically training at 60°/s which is twice that than in the current study. The isometric and isokinetic group improved to the same extent in the isometric tests, however in the isokinetic tests the isokinetic training group showed greater training improvements in comparison to the isometric group. So whilst no angular specificity or training mode specificity for isometric training was observed, it was shown training mode specificity for isokinetic training was present. However as previously mentioned elite athletes do not train to enhance their performance in strength tests, and thus the practical application of test mode specificity to sport performance must be explored.

In order to solely investigate the effect of test mode specificity it is necessary to control for the strong angle specificity effect associated with isometric training. Subsequently the study design by Folland et al. (2005) involved isometric training at four separate angles so the joint angle specificity adaptation was spread across a large range. Thirty-three males conducted a 9-week unilateral training programme of the quadriceps, with one leg performing isometric training at four angles and the opposite leg undergoing typical dynamic training. Typically larger loads would be lifted in isometric training in comparison to isokinetic training, however both legs trained at similar relative loads for the same duration. The quadriceps strength of each leg was tested isometrically (at the four angles) and isokinetically (at three velocities) pre and post training. Both types of strength training resulted in significant increases in isometric and isokinetic strength. The increase in isokinetic strength was similar in both legs, whereas isometric strength increases were significantly greater for the isometrically trained leg. The authors aimed to stipulate why isometric increases were greater for the isometrically trained leg. Whilst the authors aimed to control for joint angle specificity it is possible there may still have been some residual angle specificity effect, by which the isokinetically trained leg was disadvantaged as it trained over a greater range of motion (30-120°) compared to the isometrically trained leg (50-110°). Although relative load was controlled for, the greater absolute torques associated with the isometric training may account for the greater isometric strength gains observed, particularly as the level of loading is considered critical to the training response (McDonagh & Davies, 1984). An additional mechanism for the greater isometric gains in strength in the isometric leg could be due to a contractile mode specificity effect, with isometric training producing neurophysiological adaptations specific to isometric contractions.

Contractile mode specificity refers to whether the muscle action is performed concentrically or eccentrically, and subsequently training should reflect the contractile mode employed within the sporting action. The contractile mode specificity effect was first investigated by Hortobagyi et al. (1996). The authors tested the hypothesis that exercise training with maximal eccentric muscles actions results in greater gains in muscle strength and size than training with concentric actions. Fifteen subjects were randomly allocated to either a 12-week isokinetic concentric or eccentric training programme. The effect of each training programme was established by measuring muscle strength, muscle size and surface EMG of the quadriceps muscle. Eccentric training increased eccentric strength by 46% whereas concentric training only increased concentric strength by 13%. Eccentric training increased concentric strength by 5% and concentric training increased eccentric strength by 10%. Eccentric training increased EMG activity seven times more than concentric training. For both training modes there was no change in Type I muscle fibre percentage, but the percentage type IIa fibres increased and type IIb fibres decreased, however type II fibre area increased approximately ten times more in the eccentric than the concentric training group. It was concluded that adaptations to the training are specific to the contraction type and that eccentric muscle actions are associated with greater neural adaption and muscle hypertrophy than concentric exercise.

Balance principles

The term balance refers to the symmetry of the movement, support characteristics and muscle balance (Graham-Smith et al., 2010). Symmetry refers to whether the movement is unilateral or bilateral as in bilateral exercises there is a greater emphasis on stabilisation, which is specific to the skill of sprinting. Research has investigated the associated benefits of unilateral training in comparison to bilateral training in terms of strength gains. Exercise selection should emphasis either bilateral or unilateral movements, corresponding to what occurs in the athletic event (Gamble, 2010). Maximal voluntary strength of simultaneous bilateral exertion has been shown to be small compared to the sum of unilateral exertions. Taniguchi (1997) determined the effect of unilateral vs. bilateral training in the hand (isometric grip) and maximal isometric arm and leg extension. Following a 6-week training programme subjects saw improvements in strength tests specific to the training mode (unilateral or bilateral) undertaken. Bilateral indexes were shifted in a positive direction by bilateral training and tended to shift in a negative direction with unilateral training. It has been shown that cyclists are shown to exhibit greater overall strength when their unilateral leg press scores are summed in comparison to their bilateral leg press score, an effect known as 'bilateral deficit' (Enoka, 1997). In contrast for athletes whose skill is bilateral (e.g. rowing) show their bilateral leg press scores are greater than the sum of the unilateral leg press scores which is described as bilateral facilitation (Enoka, 1997). The results indicate there is evidence of lateral specificity in strength training, and thus the type of training selected should be specific to the sports skill.

Specificity to sprinting

Whilst all of the previously mentioned research confirms the importance of specificity in the design of strength training programmes the literature still fails to identify the level of specificity between strength training lifts and specific sports skills. It is necessary to quantify the kinematics and kinetics of the sports skill in question in order to establish whether the kinematics and kinetics of the strength training exercises are specific. Research has endeavoured to quantify the kinematic and kinetic characteristics of strength training lifts (e.g. Brown and Abani (1985); McGuigan and Wilson (1996); Escamilla et al. (2000)). However the common aim of such research is to compare two variations of a lift, often to assess potential injury risk by monitoring loads through joints, and they fail to then assess the specificity of the characteristics to a sporting skill.

Wild, Bezodis, Blagrove, and Bezodis (2011) identified the biomechanical differences between the accelerative and maximal velocity phases of the sprint to make strength training suggestions. Different methods of training can be used either to increase the rate of acceleration or the ability attain a higher maximum velocity. An understanding of the relevant biomechanical differences would allow strength and conditioning coaches to select appropriate exercises that best replicate both the kinematics and kinetics of the phase in question. The authors go on to suggest strength exercises best suited for the maximal velocity phase, but do not quantify the kinematic or kinetic specificity of these exercises to maximal sprinting.

To the authors knowledge the only research to investigate the degree of specificity of a strength training exercise to maximal sprinting was conducted by Irwin, Kerwin, Rosenblatt, and Wiltshire (2007). The authors evaluated the power clean as a sprint specific exercise with respect to the hip joint moments, work and power. The power clean is a multi-joint, multi-muscle lifting action incorporating extension at the ankles, knees and hips and includes a characteristic double knee bend (Stone, Pierce, Sands, & Stone, 2006). It has been shown to produce similar ground reaction force profiles to 10m sprinting (Tricoli et al., 2005) and power outputs that are highly correlated with the angular kinematics of the lower limb during sprinting (Okanda, Harada, & Tsuchuie, 2005). Subsequently it is often adopted as a sprint specific exercise in strength and conditioning programmes (Sheppard, 2003). Irwin et al. (2007) used a sample of four male elite track and field athletes, however they fail to report either the athletes personal best times or the horizontal velocities achieved during the sprints. Each athlete completed a power clean, an accelerating sprint and a rolling sprint from a 15m approach. Kinetic data and kinematic data were combined through inverse dynamics analysis to determine muscles moments, muscle power and muscle work. To facilitate comparisons between the power clean and sprinting the time from TD to TO was interpolated to 101 data points and values are discussed with respect to percentage of overall movement time. Peak hip kinetics were considerably greater in the power clean than either of the sprinting exercises, however this was deemed a beneficial factor based on the training principle of overload (Dick, 1980). Plotting the hip kinetics against hip angle indicated the power clean is more closely associated with the accelerating sprint than the rolling sprint. There was little eccentric loading of the hip flexors in the power clean, however as this is necessary to propel the leg forward during the swing phase of sprinting the specificity of the power clean is questioned. Furthermore the power clean is a bilateral exercise which violates the mode of training specificity principle as identified by Taniguchi (1997). However as previously discussed specificity must be considered holistically to include coordination, balance and unloading principles and it is unlikely all such elements will be targeted with gym based work alone. Thus strength-training exercises should be broken down to these respective elements when discussing specificity.

Furthermore different strength exercises will have different goals throughout a periodised training program. Young, Benton, Duthie, and Pryor (2001a) concluded that in the general preparation phase strength training exercises have a low specificity, but as the competition phase approaches the degree of specificity increases to convert the base qualities developed in the general phase (e.g. maximum strength) to the specific qualities required for maximal sprinting (e.g. power).

Summary

The methods used to enhance sprint performance are widespread and are predominantly based on coaches' knowledge and previous experience. The specificity of training is a widely recognised principle of training which is often incorrectly interpreted by coaches as selecting training methods which solely replicate the kinematics of the sports skill in question with no regards to kinetic specificity. The lack of scientific evidence behind the specificity of some training methods highlights an area for future research.

2.6 Data collection and processing

In order to answer the proposed research questions the data collected from the detailed biomechanical investigations must be designed and conducted so that they are relevant and accurate to the external environment. However due to the unique challenges associated with collecting data from an elite athlete sample the biomechanist possesses less control, both due to limitations of the sample and restrictions of the competition and/or training environment. Therefore the external and internal validity of the study design and equipment must be carefully considered. Furthermore appropriate processing techniques of the raw data must be established, specifically for the dynamic human movement of sprinting and application of inertia data.

The validity of data collection relates to whether the test or apparatus measures what it purports to measure (Thomas & Nelson, 1996). External validity of the data collection environment relates to whether the findings are applicable to the external environment, whereas internal validity refers to the validity of the measurement; are the results accurate, is there any bias or error present in findings.

There are a number of types of equipment available to investigate maximal velocity running, however the environment in which they operate often limits which equipment is used. In order to collect accurate data within a competition/training environment the choice of equipment is very important.

The use of automatic video systems is the most time-efficient method of collecting data of maximal sprinting. However this necessitates that markers are placed on a subject's body, which is time consuming and could possibly interfere with natural running gait. Furthermore this requires the testing is done indoors which could potentially interfere with the designated training session. In addition automatic video systems could not be used in competition, which is arguably when the most externally valid data could be collected. Subsequently an alternative for use with an elite athlete sample is the use of manual video systems. This allows data to be collected in an externally valid situation without interference to the athlete. Data processing allows displacement data to be derived, which can subsequently be differentiated to generate velocity and acceleration data. The video sampling rates in kinematic sprinting research range from 50Hz to 300Hz. It is important the sampling rate is at least twice as high as the highest frequency contained within the movement to ensure the aliasing effects are not present within the data (Winter, 1990). Kristianslund, Krosshaug, and van den Bogert (2012) identified gross body movements involve frequencies up to 20Hz and therefore a 50Hz sampling rate is at least twice that than the frequency of the movement. Whilst there are advantages to collecting data at higher frequencies a trade-off must be made between sampling rate and processing time – particularly when manual digitisation is being used as the processing technique.

When investigating maximal sprint velocity a critical indicator of performance is horizontal velocity. Whilst this can be established using manual video systems this is time consuming, and as field of view of the cameras increases the accuracy decreases. In order to establish maximal velocity a number of cameras would have to be used which may not be available to the researcher. A laser distance measurement device (LDM) provides instantaneous measures of velocity and can be used to identify velocity at specific distances, along with the maximal velocity achieved. The most commonly used LDM device is the Laveg (Laveg LDM 300C, Jenoptik, Germany). Arsac and Locatelli (2002) quantified the validity of the Laveg and compared distance-time results at 10-m intervals between Laveg and 50Hz video cameras. They found an average error distance between the two measures of 0.095 ± 0.060 m; however they did not report any velocity measures. A further validity study by Harrison, Jensen, and Donoghue (2005) evaluated the test re-test reliability of 300Hz video and LDM in estimating velocity-time data at different speeds. They reported both methods provided similar average velocities over 3 m sections. However velocity from the video was only based on hip marker motion and not COM and therefore its accuracy is limited. To this date a comparison between Laveg and athlete's actual COM (obtained from manual full body digitisation of video) is yet to be established.

Optojump (Microgate, Bolzano, Italy) is a new optical measurement system which uses light emitting diodes (LED's) to provide real time feedback of step length, step frequency, contact and flight times and running velocity. Glazier and Irwin (2001) assessed the validity of step length estimates from Optojump against a criterion measure of 3-dimensional video and reported that error values of 4.2 ± 23.1mm meant it lacked sufficient validity for use in motor control studies. However the authors recognised that due to its capability to provide real-time data for elite athletes, further research should be ensued. Furthermore Glazier and Irwin (2001) failed to report the validity of Optojump in determining flight and ground contact times which are key performance variables for elite sprinters (Mann et al., 1984). The validity of Optojump in determining flight times during vertical jumps was established by Glatthorn et al. (2011), who reported a good concurrent validity between Optojump and a force plate which acted as the criterion measure. Bosquet, Berryman, and Dupuy (2009) also reported a good validity of Optojump in measuring ground contact and flight time during jumping and hopping. However no published research to date has reported the validity of Optojump at assessing ground contact and flight times during sprinting.

Ground reaction force (GRF) data provide information relating to the kinetic profile of the ground contract phase of maximal velocity sprinting. GRF is collected with the use of force plates, either mounted on top of or embedded underneath the running track. The commonly used force plate to establish GRF in sprint running is a piezoelectric force plate. Piezoelectric force plates have a reported resolution of 10mN (Kistler Instruments) and an accuracy of 1% (Kerwin, 1997). A common problem with the use of force plates with elite athletes is the problem of 'targeting', which is the conscious shortening or lengthening of step length to ensure contact is made with the force plate. Challis (2001) investigated the effect of force plate targeting and reported that some temporal and GRF data was different for trials where longer or shorter than usual steps were taken, thus concluding force plate targeting may have negative effects on data collection. Existing studies have tried to overcome this problem by performing trial runs and adjusting the starting mark to ensure the athletes do not need to adjust their stride to contact the force plate. An additional option is to embed the force track within the running surface so athletes are unaware of the exact location of the plate. However a common problem associated with this is the occurrence of foot contacts occurring outside the plate boundary. This can lead to rejected trials and increases the required number of trials to allow collection of sufficient data. This can be overcome by using multiple plates mounted end-to-end and summating the forces where foot contact occurs across two plates. The sampling rate of kinetic data is normally higher than kinematic data (typically 1000Hz), and the additional processing time associated with increasing sampling rate in kinematic data is not relevant to kinetic data.

Due to the small sample sizes, studies on elite maximal sprinting typically adopt a group-based study design and either analyse data from all subjects or the mean data from sub-groups based on their personal best time (Kunz & Kaufmann, 1981) or the horizontal velocity reached. This can be useful to identify general trends, for example the kinematic variables associated with elite sprinting. Results are reported as an average for a group in an attempt to generalise to a wider population (Stergiou & Scott, 2005). Standard deviation is often reported to give an indication of variance within the sample and is typically treated as error, however inter-subject variability may be a reflection of the different individual strategies used to accomplish a task. This is particularly relevant in sprinting where differences in body stature (e.g. leg length) may govern the level of reliance on SL or SF, which was shown to be highly individualised within a sample of elite athletes (Salo et al., 2011). Only a few of the existing studies of maximal sprinting use a multiple single-subject design and subsequently they may be masking individual difference in technique or strategy. Group analysis is a useful starting point but individual differences in technique should not be ignored.

During the collection of kinematic and kinetic data noise is inevitably present within the data. Noise can arise due to both equipment and human error, particularly when data processing involves manual digitisation. The effects of noise are propagated following each differential iteration (Wood, 1982). Therefore to draw meaningful conclusions from the raw data the noise must be minimised prior to further analysis. Various smoothing methods are available, however the Butterworth filter is the most commonly used method in biomechanical investigations. A Butterworth filter can be low-pass, high-pass or band-pass, allowing designated frequencies to 'pass' through the filter whilst other frequencies are discarded. Human movement is of relatively low frequency and therefore the most commonly used filter is a 4^{th} order low-pass Butterworth filter. The selection of the optimal cut-off frequency is commonly using Winter (1990) residual analysis technique. This involves visual inspection of a residual frequency graph to select the most appropriate cut-off frequency.

Many of the common variables reported in the literature of elite maximal sprinting refer to the centre of mass, typically the resultant horizontal and vertical velocities of the COM and the overall displacement of the COM during a gait cycle. In order to calculate the accurate position of the COM the kinematic data must be combined with body segment inertial parameters. The estimation of such parameters has been performed using numerous methods and various models have been developed. The earliest model by Dempster (1955) established segment masses and lengths from dissected cadavers, however Yeadon, Challis, and Ng (1994) noted the use of cadaver data to extrapolate to healthy sporting populations may lead to errors due to physiological differences in body size and composition. Mathematical modelling has been employed to establish more detailed inertial parameters (e.g. COM location of individual segments) from the cadaver-based studies (Yeadon, 1990). Whilst the accuracy of the method is reportedly high (predicting body mass to within 3%), it is a time consuming method and makes assumptions such as that of uniform density within a segment (Yeadon, 1990). The most accurate method available are medical imaging techniques, such as gamma-mass scanning employed by Zatsiorsky and

Seluyanov (1983) which enables the tissue distribution within the body to be established. Most relevantly Zatsiorsky and Seluyanov (1983) used a young athletic population which enhances the external validity of their findings to the current research in comparison to the Dempster (1955) data. However de Leva (1996) highlighted the Zatsiorsky and Seluyanov (1983) model relates to bony landmarks of segments as opposed to joint centres as commonly reported in biomechanical data. Thus de Leva (1996) presented a revised model with adjusted values which relate to joint centres. However the adapted values by de Leva (1996) used different definitions of the distal endpoint of the shank and the proximal endpoint of the foot segment to that of Zatsiorsky and Seluyanov (1983). Subsequently recent research of sprinting (e.g. Hunter et al. (2004c), Bezodis (2009)) has used an adapted model which uses the de Leva (1996) model with the exception of the foot segment for which they use the values calculated by Dempster (1955).

2.7 Chapter summary

The literature review has summarised the existing kinematic and kinetic research on maximal velocity sprinting at velocities >10.0m/s. The review exposed a lack of detailed kinematic research regarding the technique of elite sprinting due to the lack of access to elite athlete populations and the difficulties of obtaining such information during competitive environments. Furthermore the limitations imposed by laboratory testing mean the kinetics of sprinting at these velocities is non-existent within an elite athlete sample. Whilst running drills and strength training programmes are commonly used by elite sprinters there has been a disregard for scientific evaluation of the specificity of sprint training methods. Running drills have only received attention in the coaching literature and their similarity to maximal running is yet to be established. Similarly whilst the specificity of training is recognised as a critical principle in strength training the academic literature is yet to quantify the specificity of common resistant training exercises to maximal sprinting. Finally the review highlighted there was discrepancy in the most valid and reliable data collection methods for maximal sprinting, which is particularly relevant when using elite athletes populations when data collection methods are often confined by the sample and the setting (for example in competition).

CHAPTER 3 – ASSESSMENT OF METHODS USED TO EVALUATE MAXIMAL VELOCITY SPRINT RUNNING

3.1 Introduction

The evaluation of sport-specific performance measures can provide fundamental information to a coach, athlete and sports scientist on an athlete's response to a training programme (Smith, Norris, & Hogg, 2002). When working with a sample of elite athletes within an applied environment such evaluation of sport-specific measures is often the responsibility of a sports scientist (typically a biomechanist/performance analyst). However due to the nature of the sample this often incurs limitations. Elite athletes are largely unable and unwilling to change their training schedule for the sake of research (Kearney, 1999). Therefore the most practical tests for elite athletes are those that can be administered in the training or competition environments, and must be non-invasive and not interfere with the execution of the training session. Furthermore a unique role of an applied sports scientist is the capacity to offer instant feedback to coaches and athletes. Hence coaches favour technology that can provide immediate data as it facilitates the use of objective feedback to evade a constant reliance on subjective feedback.

In sprinting the aim is to cover a distance in the shortest possible time, and thus the critical determinant of performance is running velocity. Hence the monitoring of horizontal velocity, along with the factors which influence it, is of importance to a sprint coach monitoring an athlete's development. Due to the numerous types of gait analysis equipment there are likely a number of methods available and the selection of the most appropriate technique must be based on the advantages and disadvantages of the equipment required. Furthermore the limitations on equipment permitted in the competitive setting often means the equipment and methods used in the training environment cannot be replicated within competition. Subsequently it is necessary to establish the validity and reliability of each of the measurement techniques used both in training and competition to assess whether different methods can be used interchangeably.

The validity associated with the collection of data relates to whether the test or apparatus measures what it purports to measure (Thomas & Nelson, 1996). Validity is composed of internal validity; are the results obtained accurate or do they contain measurement error/bias and secondly external validity; can the results obtained be extrapolated to an applied setting?

The gait analysis technology that is designed for use within an applied environment inherently has a high external validity. However Atkinson and Nevill (2001) recognised that when striving to maintain external validity by collecting data within training or competition the internal validity of a research study can often be negatively affected. As new technologies are developed they are typically compared to optoelectronic systems to verify their internal (or concurrent) validity. Concurrent validity refers to the agreement between the observed value and the true or criterion value of a measure. The optoelectronic systems act as the criterion measure in order to calculate the magnitude of measurement error associated with the new equipment. Yet when working with elite athletes laboratory testing is rarely used, and subsequently comparing the validity of equipment to that of laboratory settings lacks significance. A more meaningful measure of validity to an applied biomechanist is to establish the validity of technologies within the environment they will be employed. An applied biomechanist is typically able to evaluate performance both within a training and competitive environment. In most cases the aim is to improve competitive performance, and therefore the most valid environment to evaluate an intervention/training programme would be to analyse an athlete within competition. On the other hand, analysing an athlete in the training environment increases the number of available testing opportunities, and can be used to monitor an athlete throughout a season when they are not competing. Therefore in order to make comparisons between data collected within both training and competition the experimental set-up must remain consistent and be performed with precision in order to minimise the measurement error, and thus maximise internal validity.

Reliability refers to the reproducibility of values of a test, assay or other measurement in repeated trails on the same individuals. A high level of reliability means a biomechanist and coach can confidently detect small changes in an athlete's performance, and use smaller sample sizes in research (Hopkins, 2000). However errors in biomechanical measures are inevitable due to equipment limitations and the biological variation of the subject, and subsequently some variables may not be suitable for identifying small changes in performance (Hunter, Marshall, & McNair, 2004b). Reliability can be enhanced by using the average score of multiple trials, but the additional time in processing multiple trials is disadvantageous. Furthermore due to nature of elite athletes training it is often the case that they only complete one trial during a session, and notably often only one race per competition, and therefore taking an average is not possible. Therefore it is important to establish the reliability of the methods beforehand to establish whether one measure can be a true representation of an athlete's performance. A common method used by an applied biomechanist is manual digitisation of video to establish kinematic gait variables such as joint angles and COM profiles. The use of on-body markers is not practical when working with elite athletes due to the time associated with affixing markers, and subsequently manual digitisation is based on the researcher's individual judgement of joint locations. Subsequently it is critical to establish the interrater and intrarater reliability of manual digitising to identify the typical level of error associated with this process. If necessary the reliability of manual digitisation can be enhanced by digitising the same trial a number of times and taking an average – however this greatly increases the post-processing time.

The deterministic models discussed in the literature review define the SL, SF, FT and GCT as the key performance variables that dictate horizontal velocity. Prior to using these variables to assess performance it is necessary to establish the validity and reliability of the techniques used to measure them.

Video analysis is the most inexpensive and readily available of gait analysis tools and is a commonly adopted approach for analysis of sprinting. Advances in frame rate and video resolution continue to improve its accuracy as an analysis tool. Furthermore its ability to be used in both training and competition favours its use by many coaches and biomechanists. Video can be used to calculate SL, along with GCT and FT, which can then determine SF. Further, if a fixed camera is used (combined with a calibration file), manual digitisation can be employed to obtain more detailed kinematics along with a COM profile, which can then be differentiated to calculate running velocity. Common problems associated with video analysis are both the small image and the variable size of the image if a panning technique is used. Manual digitising induces the possibility of human error and greatly increases the processing time. Furthermore, to obtain accurate step lengths it is necessary for additional markings to be placed on the track using adhesive tape which is not always feasible in a competition environment.

Many biomechanical variables are sensitive to change in speed and therefore a measure of running velocity is valuable information for a biomechanist, and can also be used by coaches as an objective measure of performance. This is commonly obtained using timing gates which estimate velocity by measuring the time taken to cover a set distance. Timing gates are advantageous due to the ease of set-up; however errors occur when different parts of the athlete's body break the beam, and they only provide a measure of average velocity over a distance as opposed to instantaneous velocity. Laser measurement devices (LDM) measure the time delay of reflected pulsed infrared light to determine the instantaneous velocity of an object either moving towards or away from the laser. Laser measurement devices provide a non-obtrusive measure for determining horizontal velocity that is immediately available to a coach or athlete. Feedback includes split times, velocity and acceleration at pre-defined distances from a reference line (typically the start line), along with a velocity profile of the whole sprint. This method can be employed during competition (with agreement from competition officials), however it requires that the biomechanist is directly in line with the oncoming/outgoing athlete and requires a non-interrupted line of sight for the laser beam. A limitation of LDM is the displacement data is based on a point on the subject's body which is tracked by the operator rather than the athlete's actual COM. To identify the error of the Laveg device Arsac and Locatelli (2002) compared distance-time results at 10-m intervals between a Laveg sampling at 50Hz (Laveg Sport, Jenoptik, Jena, Germany) and 50Hz video cameras. They found an average error distance between the two measures of 0.10 ± 0.06 m; however they did not report any velocity measures. Türk-Noack (1994) reported an average velocity error of <2% for Laveg, and the reliability in velocity measures across repeated running trials gave a typical error of 0.05m/s and in intraclass correlation of 0.98 (Duthie, Pyne, Marsh, & Hooper, 2006). A further validity study by Harrison et al. (2005) evaluated the test re-test reliability of 300Hz video and LDM in estimating velocity-time data at different speeds. They reported both methods provided similar average velocities over 3 m sections. However velocity from the video was only based on hip marker motion and therefore its accuracy is limited. To this date a comparison between Laveg and athlete's actual COM (obtained from manual full body digitisation of video) is yet to be established.

Optojump (Microgate, Bolzano, Italy) is a new optical measurement system which uses light emitting diodes (LED's) to provide real time feedback of step length, step frequency, contact and flight times and running velocity. The real time feedback means it is a useful tool for coaches and can also provide immediate information on asymmetry between left and right legs. However disadvantages associated with the system are the time-consuming set-up, along with the necessity for a power supply which must cross either the start or finish line. The main limitation is it cannot be used in a competitive environment as it requires 'springboards' to be placed either side of the running lane which would be intrusive to athletes in adjacent lanes. Glazier and Irwin (2001) assessed the validity of step length estimates from Optojump against a criterion measure of 3-dimensional video and reported that error values of 4.2 ± 23.1mm meant it lacked sufficient validity for use in motor control studies. However the authors recognised that due to its capability to provide real-time data for elite athletes, further research should be ensued. The authors used an Optojump system with a 3cm resolution, however systems with 1cm resolution are available which would likely increase the accuracy of step length estimates. This research failed to report the validity of Optojump in determining flight and ground contact times which are key performance variables for elite sprinters (Mann et al., 1984). The validity of Optojump in determining flight times during vertical jumps was established by Glatthorn et al. (2011), who reported a good concurrent validity between Optojump and a force plate (which acted as the criterion measure). Bosquet et al. (2009) also reported a good validity of Optojump in measuring ground contact and flight time during jumping and hopping. However to date no published research has reported the validity of Optojump at assessing ground contact and flight times during sprinting.

Subsequently the purpose of this research is to establish the validity and reliability of video cameras, LDM and Optojump, with the primary aim of establishing whether the three methods can be used interchangeably to assess the key gait variables measured, and subsequently whether data collected from training and competition environments can accurately be compared.

3.2 Methods

Fifteen experienced athletes (10 males and 5 female) volunteered as participants for the study. Athletes were a combination of sprinters (100m, 200m, 400m), pole vaulters, one 400m hurdler and one decathlete, and had competed in their respective disciplines on average for 7 years. The men were 23.8 ± 4.7 years old (mean ± SD), were 1.84 ± 0.05 m in height and had a mass of 77.4 ± 5.9 kg. The respective values for the women were 22.0 ± 1.8 years, 1.66 ± 0.04 m and 58.6 ± 5.22 kg. Subjects wore their own running attire and running spikes. Whilst the ability level of each athlete (along with track and field discipline) would affect the velocity magnitude it was deemed this would not influence the study outcome in which the aim was to compare gait variables across different systems. Ethical approval was obtained from the University of Salford ethics committee and all subjects provided written informed consent before the onset of the data collection.

Prior to commencement of data collection participants completed an individual warm-up. Participants then completed a minimum of three 60 m running trials (followed by a 30m deceleration) with approximately 7 minutes rest between trials. Participants ran on a synthetic indoor running track at a self-defined speed (however participants were requested to run at near maximal speed).

The measurement set-up is presented in Figure 3-1. Gait variables were measured as subjects ran through a 30m-measurement zone. To ensure athletes reached maximal velocity within the measurement zone they started 30m back from the start of the measurement zone, thus the zone represented 30m-60m of the total 60m repetition.

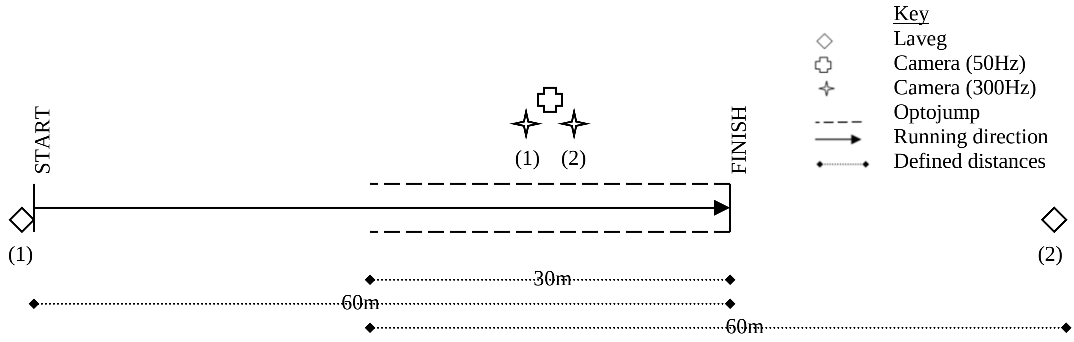


Figure 3-1 Experimental set-up of Study 1

Two laser measurement devices (Laveg LDM 300C, Jenoptik, Germany) were used to obtain distance and velocity measurements during all running trials. The laser provides a linear distance measurement at a sampling frequency of 100Hz. Each Laveg was calibrated so zero represented the start of the 30m measurement zone. Each Laveg was located in the centre of the running lane. Laveg (1) was at a height of 1.20 m (all measurements are taken from the centre of the lens) and 31 m behind the start of the measurement zone and Laveg (2) was at a height of 1.20m and 60 m in front of the start of the measurement zone. The laser beams were directed at the lower part of the runners back and the torso for the rear and front view Lavegs respectively.
Two fixed high-speed video cameras (Casio EXILIM EX-F1) operating at 300fps were located perpendicular to the measurement zone at a distance of 9.5 m from the centre of the running lane and a height of 1.13m. Placement of the cameras was such that the field of view was from 42 m to 52 m of the measurement zone (each camera's field of view was 6 m with a 2 m overlap). This equated to the field of view of Camera (1) being 42-48m and the field of view of Camera (2) being 46-52m of the full repetition distance. An additional panning video camera (Sony HVR-A1E) operating at 50fps was placed in-between the two fixed cameras at a height of 2.00 m to obtain panning footage of the full 30m measurement zone. To obtain measures of step lengths from the panning camera white tape was placed at 1m intervals on either side of the running lane for the full 30 m measurement zone. A total of thirty Optojump photoelectric cells, which consist of two parallel bars (one transmitter and one receiver, each measuring 100 x 4 x 3cm) were placed on either side of the running lane for the entire 30m measurement zone. The transmitter contains 100 LED's which are positioned 0.3cm from the ground at 1 cm intervals. Optojump was connected to a laptop via a USB port and the proprietary software (Optojump software, version

1.5.1.0) was used to quantify GCT, FT, SL, SF and horizontal velocity. The only additional input required from the researcher was to define which foot contacted first within this measurement zone; this was identified using the existing video footage.

The Laveg data was processed using the programme associated with the device (das3e). Displacement-time data were captured at 100Hz and treated with a 51-point moving average (Phillips, 2011), and from this an instantaneous velocity trace was derived. The velocity trace was used to establish the maximum velocity that occurred within the 30m measurement zone. This was used to identify the fastest repetition for each athlete, and this repetition was then used for all further analysis.

The fixed high-speed cameras (300fps) were used to determine GCT and FT for the 10m field of view of the cameras (42-52m). Contact time was measured from the 1st frame when the foot made contact with the ground until the frame when the foot had broken contact with the ground. Flight time is the 1st frame when the foot is definitely no longer in contact with the ground until the frame when the opposite foot contacts the ground. Step frequency was calculated using the equation below (Equation 1):

$$SF = \frac{1}{GCT + FT}$$

Equation 1 Calculation of step frequency

The panning video (50fps) was used to determine step lengths using the methods detailed by Chow (1993). The SL and SF data were then combined to give a velocity estimate using the equation below (Equation 2):

$$V = SL \times SF$$

Equation 2 Calculation of velocity

Flight and ground contact time, step frequency, step length and velocity were obtained from the Optojump 3.0 software (version 1.5.1.0) for the full 30m measurement zone.

The fixed camera (300fps) was also used for manual digitising. Whole body COM displacement was calculated using inertia modelling procedures. Quintic

Biomechanics (version 9.03v17) was used to digitise the body to determine whole body COM displacement. An 18-point, 14-segment model was employed, digitised points were: vertex, C7, greater tuberosity of humorous, elbow, wrist, third metacarpal, greater trochanter of femur, lateral epicondyle, lateral malleolus, 5th metatarsal joint. No markers for landmarks were used due to the errors associated with surface marker movement along with the difficulties associated with using markers with an elite sample. For each athlete two full steps (from TO to TD) were digitised at 300Hz, with an additional 30 frames before the first frame of interest and after the last frame of interest to act as 'padding' to reduce the effects of distortion during the filtering process. Raw coordinate data was smoothed using a 4th order low pass Butterworth filter with a cut-off frequency of 11Hz. The optimum cut-off frequency for each data point was identified using residual analysis (Winter, 1990). The inertial parameters of de Leva (1996) were used to calculate the COM position. Displacement values were differentiated using second central difference equations (Miller & Nelson, 1973) to determine a COM velocity.

As aforementioned it is not relevant to compare each of the methods with a criterion measure (such as optoelectronic systems), therefore it is the agreement between methods which must be established. In order to quantify the level of agreement the Bland-Altman method with 95% limits of agreement (Equation 3) was employed between each of the comparisons listed below:

Table 3-1 Matrix for comparisons for each analysis method (rows) and gait variables (columns)

		FT	GCT	SF	SL	Maximum velocity
Laveg (100Hz)	Rear					x
	Front					x
Optojump		x	x	x	x	x
Camera (300fps)		x	x	x		x
Camera (50fps)					x	

$$\textit{Boundaries of agreement} = \delta \pm (1.96 \times \sigma)$$

where δ = mean of the differences between data sets

σ = standard deviation of difference between data sets

Equation 3 Calculation of boundaries of agreement (Bland & Altman, 1986)

Within the 15 trials there were 61 pairs of FT estimates, 65 pairs of GCT estimates, 148 pairs of SL estimates, 59 pairs of SF estimates and 15 pairs of maximum velocity estimates. In order to establish the digitising reliability of each researcher (intrarater), five trials were selected at random and digitised a total of three times separately by two researchers. The re-digitised trials were spread out over the whole digitising process to avoid a learning effect. Based on the existing literature a number of key kinematic variables were calculated from the raw coordinate data to include distance, velocity, angle and angular velocity variables. From this the mean difference between each of the three digitisations was used to establish a level of digitising reliability for each variable independently (Equation 4). This gives an indication of the absolute error associated with the calculation of each variable, and subsequently the magnitude of difference required before a meaningful difference can be inferred.

$$\sum \textit{difference} = \frac{(= d1 - d2) + (d2 - d3) + (d1 - d3)}{3}$$

where d=digitisation of individual trial (three digitisations per trial)

Equation 4 Calculation of intrarater digitising reliability

3.3 Results & Discussion

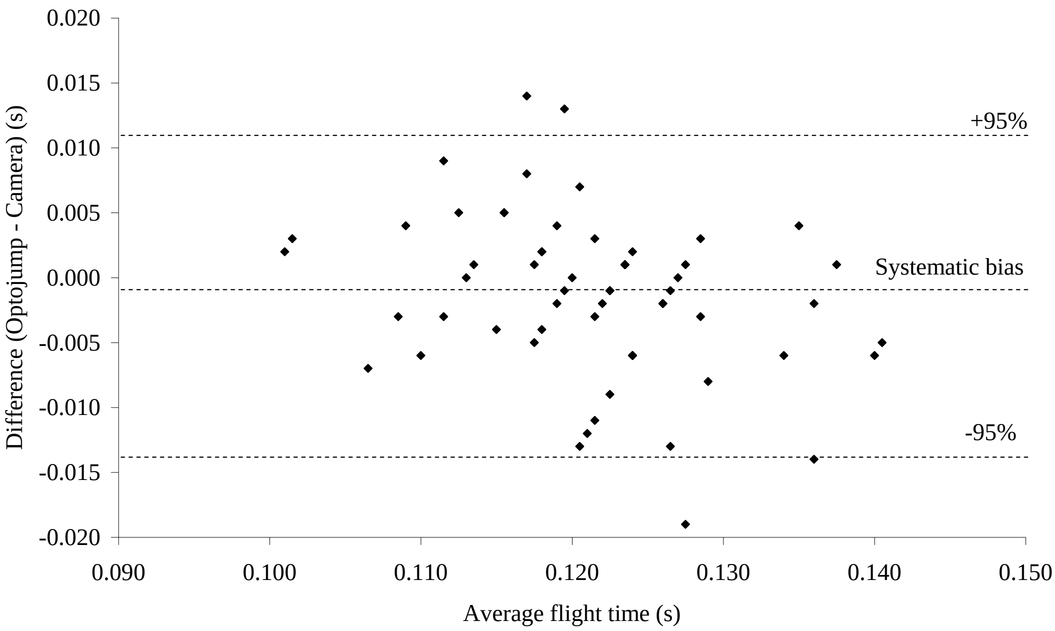
The mean and standard deviation of each of the gait variables calculated by each analysis method is presented in Table 3-2.

Table 3-2 Mean (±SD) for each of the gait variables (columns) for each analysis method (rows). Systematic bias, random error, confidence intervals and difference as a percentage of the mean are reported

	FT (s)	GCT (s)	SF (Hz)	SL (cm)	Maximum velocity (m/s)
	n=61	*n=65*	*n=59*	*n=148*	*n=15*
Optojump	0.121 (0.008)	0.112 (0.007)	4.31 (0.19)	211 (14)	9.22 (0.56)
Camera (300fps)	0.122 (0.010)	0.110 (0.009)	4.31 (0.17)	-	9.20 (0.55)
Camera (50fps)	-	-	-	213 (15)	9.45 (0.74)
Rear Laveg (100Hz)	-	-	-	-	9.16 (0.52)
Front Laveg (100Hz)	-	-	-	-	9.36 (0.53)
Systematic bias	-0.001	0.003	0.00	-2	0.20
Random error	0.006	0.007	0.15	4	0.12
+ 95% CI	-0.014	-0.0106	-0.03	-9	0.43
- 95% CI	0.011	0.016	0.3	5	-0.03
Difference as % of mean	1.12	2.45	-0.02	0.98	0.02

Both flight time and ground contact time estimates were compared between Optojump and the high-speed fixed camera (300fps). The Bland-Altman plots indicate both systematic and random error exists between the Optojump system and high-speed camera (Figure 3-2). The resulting error interval for flight time was -0.001 ± 0.006s, indicating a positive systematic bias of the high-speed camera. The resulting error interval for ground contact time was 0.003 ± 0.007s, with a systematic bias indicating high-speed cameras underestimate ground contact time. The systematic and random error did not display heteroscedasticity that is they were not proportionate to the flight time or ground contact time, indicated by the random scatter of points on the graph. The systematic overestimation and underestimation of FT and GCT respectively by the high-speed camera is likely to be related to the methodology used to categorise them. A small size and/or poor quality of the image may obscure the exact frame when touchdown and toe-off occurs. Furthermore the identification of touchdown and toe-off are subject to individual judgment by the researcher. The error interval for flight time was 0.001s, which actually equates to less than one frame of video when filmed at 300fps. As the systematic error was consistent towards overestimating flight time and underestimating ground contact time this may be attributed to the researcher's estimation of when touchdown and toe-off occur. The researcher judged touchdown as when the foot had clearly contacted the ground, whereas Optojump identifies touchdown to occur when the LED lights in the springboards are interrupted. Thus it is possible that the researcher's estimation of touchdown may be one frame later. When expressed as a percentage of the mean it equates to only a 1.12% error. The discrepancy in identifying the point of touchdown between high-speed cameras and Optojump will also justify why individual judgment consistently underestimated ground contact by 0.003s, or one frame of 300fps video. If the researcher judges ground contact to occur one frame later than the Optojump system, not only will this increase individual estimation of flight time but will subsequently underestimate individual estimation of ground contact time. Furthermore the point of toe-off is also subject to individual opinion and will be subject to the same variances as discussed with touchdown. However when expressed as a percentage of the mean it reflects an error of only 2.45%. The limits of agreement indicate the area where we would expect differences to lie and thus are not of practical importance.

a)



b)

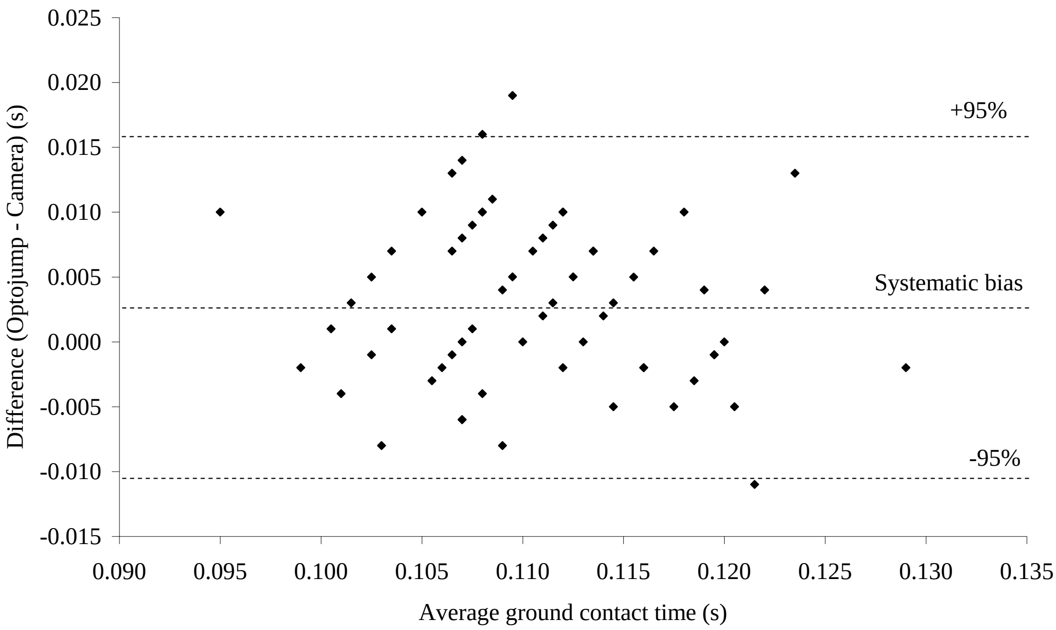


Figure 3-2 Bland-Altman plots illustrating systematic bias and 95% limits of agreement between Optojump and Video camera (Hz) for a) flight time and b) ground contact time. The mean value between the 2 methods is plotted on the x-axis, and the difference between the 2 methods (Optojump – Camera) is plotted on the y-axis.

The FT and GCT obtained from the high-speed camera were combined (Equation 2) to facilitate a comparison of step frequency to that measured by Optojump. A Bland-Altman plot reveals no systematic bias in SF between the two techniques, in spite of the systematic bias identified for GCT and FT. This can be attributed to the equation used to calculate step frequency. By summing the FT and GCT the overestimation of FT by high-speed fixed cameras is counteracted by the underestimation in GCT, thus equating to a similar measure of SF.

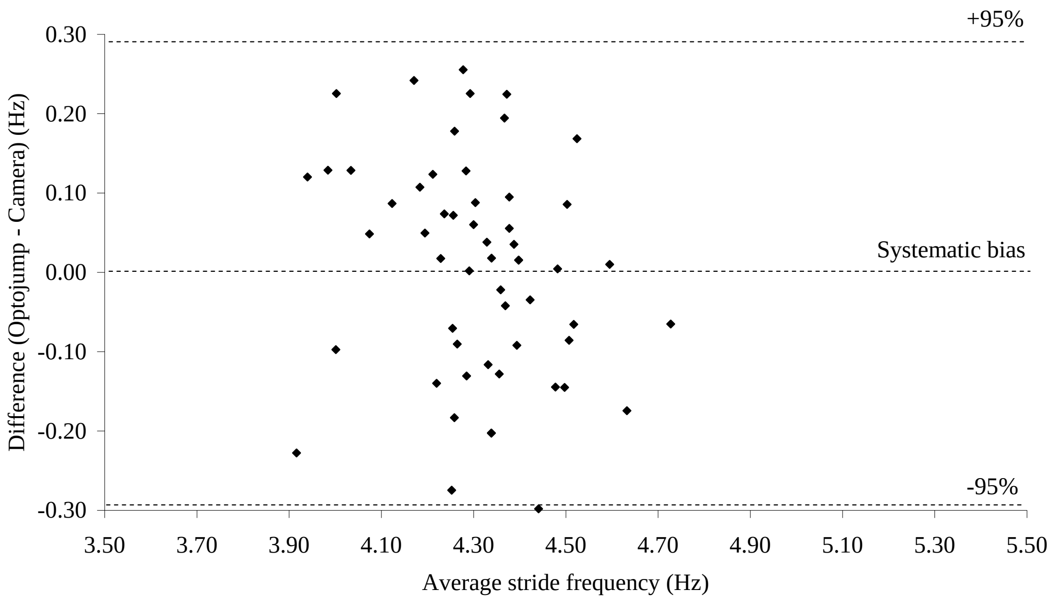


Figure 3-3 Bland-Altman plots illustrating systematic bias and 95% limits of agreement between Optojump and cameras (300Hz & 50Hz) for estimating step frequency. The mean value between the two methods is plotted on the x-axis, and the difference between the two methods (Optojump – Cameras) is plotted on the y-axis.

Step length estimates were compared between Optojump and measurements obtained from a panning camera filming at 50fps. The resulting error was -2 ± 4cm, and the Bland-Altman plot reveals that neither random or systematic error are affected by the magnitude of the step length as indicated to the random scatter of data points (Figure 3-4). As with the determination of flight and contact time, the step length estimates obtained from panning video cameras are affected by the quality and size of the video image. The mean error takes into account all step lengths obtained from the video (a distance of approximately 20m), and does not distinguish between the step length estimates taken at a distance and those taken closer to the position of the camera.

Furthermore it should be reiterated that this method is still not possible within competition due to restrictions of using tape alongside the track.

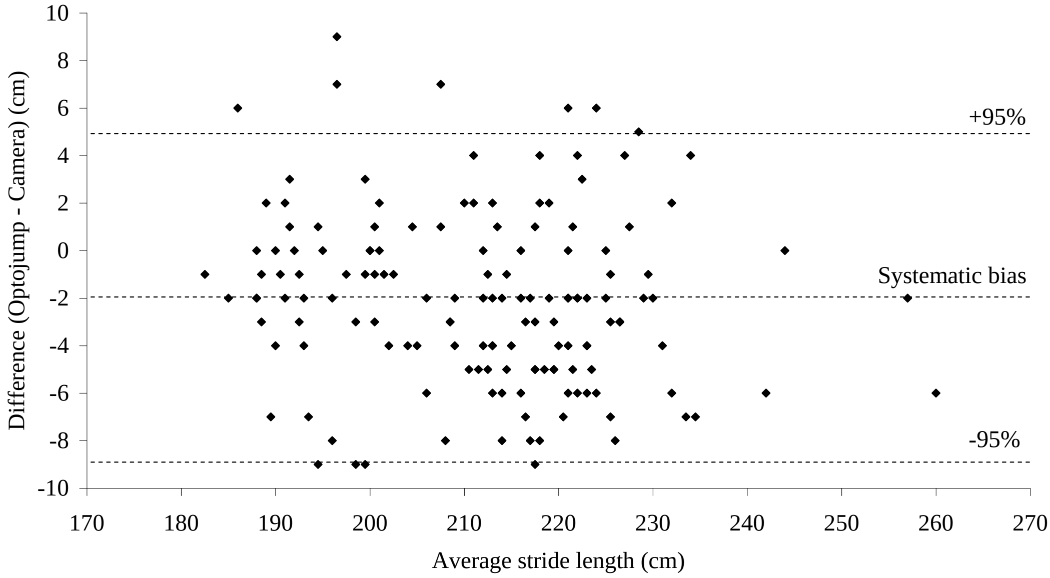


Figure 3-4 Bland-Altman plots illustrating systematic bias and 95% limits of agreement between Optojump and Video camera (50 Hz) for estimating step length. The mean value between the two methods is plotted on the x-axis, and the difference between the two methods (Optojump – Camera) is plotted on the y-axis.

As aforementioned horizontal velocity is a critical performance determinant of sprinting, and further its influence on other biomechanical variables warrants its importance to be monitored both in training and competition. For the purpose of this thesis a measure of horizontal velocity will be used to quantify the maximum speed reached within a training repetition/race, and therefore the accuracy of each of the measurement techniques to identify maximum horizontal velocity was compared. Both in training and competition the position of the Laveg speed gun (either from the rear or front) is limited by available space and/or competition rules. Subsequently it was necessary to establish the validity of two Lavegs (one from the front and one from the rear) in identifying maximum velocity. A margin of error of 0.200 ± 0.116 m/s was reported for maximum velocity findings. Of interest is the improvement in agreement between the two Lavegs as average velocity increased (Figure 3-5), indicated by a greater cluster of points towards the mean as the graph moves from left to right. This is of relevance when working with elite athletes as the velocities reached often exceed 10.0 m/s. The difference between front and rear Lavegs can potentially be explained by the difference in the tracking point used by each Laveg. The rear Laveg is focused on the lower back of the athlete, whereas the front Laveg focuses on the torso of the athlete. Due to the depth of an athlete's body these two positions may be approximately 20cm in difference. Consequently the front of an athlete will pass through each distance interval a fraction before the rear of the athlete, leading to a systematic offset in speed measurements between the two Lavegs. As each Laveg was controlled by a different operator slight differences may be due to individual variance in tracking technique. Further, only a sample of 15 was possible which is below the threshold recommended by Altman and Bland (1991) and therefore it is proposed this comparison is repeated with a larger sample size. When represented as a percentage error this equates to only 0.22% between the two positions. Subsequently it is deemed appropriate to use either position interchangeably, dependent on which is most appropriate/possible within the training/competition environment. In most cases the rear position is favoured to minimise interruption of the laser from the arms swinging across the body, and additionally to minimise obstruction to the oncoming athlete. Subsequently for the remainder of this study the data from the rear Laveg will be utilised.

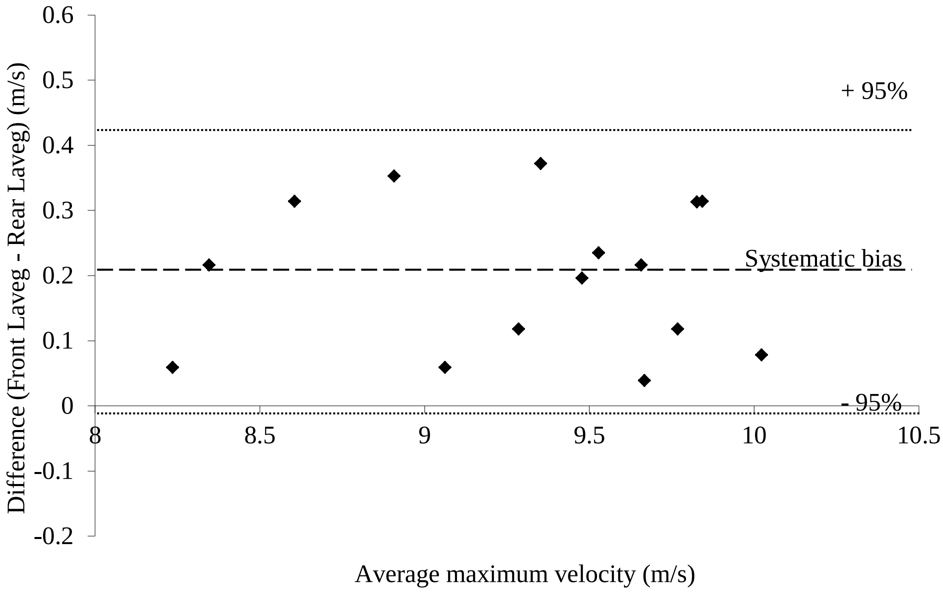


Figure 3-5 Bland-Altman plot illustrating systematic bias and 95% limits of agreement between Laveg from the front and Laveg from the rear for maximum velocity. The mean value between the two methods is plotted on the x-axis, and the difference between the two methods (Front Laveg – Rear Laveg) is plotted on the y-axis.

Each of the four different measurement techniques were compared to give a total of 6 comparisons (Table 3-3). In order to facilitate comparisons for maximum velocity between each type of the equipment the maximum velocity achieved between 12-22m was identified as this reflects the field of view of the high-speed fixed cameras. Figure 3-6 shows a Bland-Altman plot with 95% confidence limits for each of the 6 comparisons.

Table 3-3 Comparison data between each of the four analysis techniques (Laveg, Optojump, manual digitisation and panning video) (six comparisons in total) of maximum velocity (m/s). 95% confidence intervals are also presented.

	Comparison					
	1	2	3	4	5	6
Measure 1	Laveg	Laveg	Laveg	Manual digitisation	Manual digitisation	Optojump
Measure 2	Manual digitisation	Optojump	Panning camera	Optojump	Panning camera	Panning camera
Systematic bias (m/s)	-0.043	-0.064	-0.294	-0.021	-0.251	-0.230
Random error	0.193	0.122	0.390	0.223	0.464	0.455
+ 95% CI	0.334	0.175	0.471	0.416	0.658	0.661
- 95% CI	-0.421	-0.304	-1.060	-0.458	-1.160	-1.121
Difference as % of mean	-0.5	-0.7	-3.1	-0.2	-2.6	-2.4
Effect size (ES)	0.05	0.12	0.47	0.04	0.39	0.35
Definition (Cohen, 1988)	Small	Small	Moderate	Small	Moderate	Moderate

The results of the current study indicate that the maximum velocity of the COM identified by manual digitisation (9.20m/s) is comparable to that measured by the Laveg (9.16m/s) (Comparison 1). The systematic bias is small (-0.043), which is indicated on the Bland-Altman as an even distribution around the zero line. The plot also shows the magnitude of velocity does not appear to have an effect on the level of agreement between the two methods indicated by the random scatter of points. In order to discuss the results in the context of practical application the difference between the two methods was represented as a percentage of the mean, and additionally the effect size was calculated. The difference between Laveg and manual digitisation at identifying maximum velocity represented only 0.5% of the mean, and the narrow confidence intervals suggest that comparisons between these two methods can be made confidently. Differences in the two measures may be attributed to their respective sampling rates of 300fps and 100Hz. Further, a low-pass filter was applied to the manual digitisation; whereas a 51-point moving average was applied to the Laveg. As discussed a comparison of Laveg to high-speed video was previously conducted by Harrison et al. (2005). However the authors only used the motion of the hip marker in the video rather than a true indication of COM. Harrison et al. (2005)

compared average velocities over a 10m distance rather than instantaneous maximal velocity and thus prevents any further comparisons with their findings. This shows that if Laveg is not available the manual digitisation can still give a measure of the maximum velocity, however it should be noted that this will only be based on the maximum velocity in the field of view of cameras, and may fail to record the actual maximal velocity of the entire repetition.

The second comparison between Laveg and Optojump found Laveg reported a lower average value of maximum velocity (9.16m/s) than Optojump (9.22m/s). There is a slight positive systematic bias of Optojump with 60% of values lying below the zero line indicating Optojump estimated a greater maximum velocity than Laveg. However the narrower confidence intervals (see Bland-Altman plot) show the agreement between Laveg and Optojump is closer than the comparison of Laveg and manual digitisation. This is an interesting finding when considering the opposing sampling rates of the two methods. Laveg provides an instantaneous measure of velocity at 100Hz, whereas Optojump only calculates velocity per gait cycle (from the equation SL x SF). The Laveg will therefore be able to identify fluctuations in velocity as a result of the phase of the gait cycle, whereas Optojump will only report a mean value for an individual step. Furthermore over a 10m period the Laveg may provide approximately 100 measures of velocity (if an individual were running at 10m/s), whereas Optojump may provide only 4 (if an individual has a step length of approximately 2.5m). Subsequently it would be expected that Optojump will fail to identify the true level of maximum velocity. However when expressed as a percentage of the mean the difference between the two methods is only 0.7% which is deemed an acceptable level of error, and represents a small effect size as defined by Cohen (1988).

The final comparison of Laveg was to the comparison of maximum velocity from the manual identification of SL and SF from a combination of panning and fixed video (Comparison 3). The Bland-Altman plot shows the majority of points lie below the x-axis, indicating a systematic bias (-0.294) with video estimating a higher level of maximum velocity compared to Laveg. The large scatter of points and subsequently wide confidence intervals imply a poorer level of precision than the previous two comparisons. This is reflected in a mean percentage error of 3.1%, however this is still classified as small by Cohen (1988). As video utilises the same calculation (SL x SF) as Optojump one would expect a similar level of agreement to Comparison 2. However the difference in agreement can be explained by the significant difference in the step length and ground contact time estimates between Optojump and the panning and fixed videos respectively.

By comparing the levels of agreement between Laveg and the other three methods we can begin to draw conclusions on which is the ‘true’ measure. Based on the greater levels of agreement in Comparison 1 and 2 compared to Comparison 3 it is proposed that it is potentially the video measurement of maximum velocity which is erroneous. Later comparisons using this (Comparison 5&6) will be able to confirm this hypothesis.

The level of agreement between manual digitisation and Optojump (Comparison 4) produces the smallest mean difference (-0.021m/s) of all comparisons. Observation of the Bland-Altman plot shows a random scatter of points above and below the x-axis, thus indicating a consistent systematic bias is not present. Narrow confidence intervals indicate a high level of agreement between these two methods, and provide evidence they can be used interchangeably to define maximum velocity.

As aforementioned the wide confidence intervals in Comparison 3 highlighted the calculation of maximal velocity from the combination of panning and fixed video as a potential problematic method. The comparison of this method with manual digitisation (Comparison 5) and Optojump (Comparison 6) provided very similar levels of mean difference, confidence intervals and standardised difference of the mean (Table 3-3). The standardised difference of the mean for Comparison 5 was 0.65 and for 0.61 for Comparison 6 – both of which are classified as ‘moderate’. Inspection of the Bland-Altman plots indicates a large scatter of points, accompanied by wide confidence intervals. Thus it is concluded that using SL and SF derived from video is not an acceptable method by which to define the instantaneous maximum velocity. The inaccuracies associated with this method can be attributed to the equation used. Each variable within the equation (SL, SF) is obtained from human judgement, and thus any errors within each of the individual variables will be propagated when multiplied together. Thus whilst it is deemed acceptable to have these levels of error when looking at the individual variables, it is proposed that different methods are used to obtain a measure of maximum velocity.

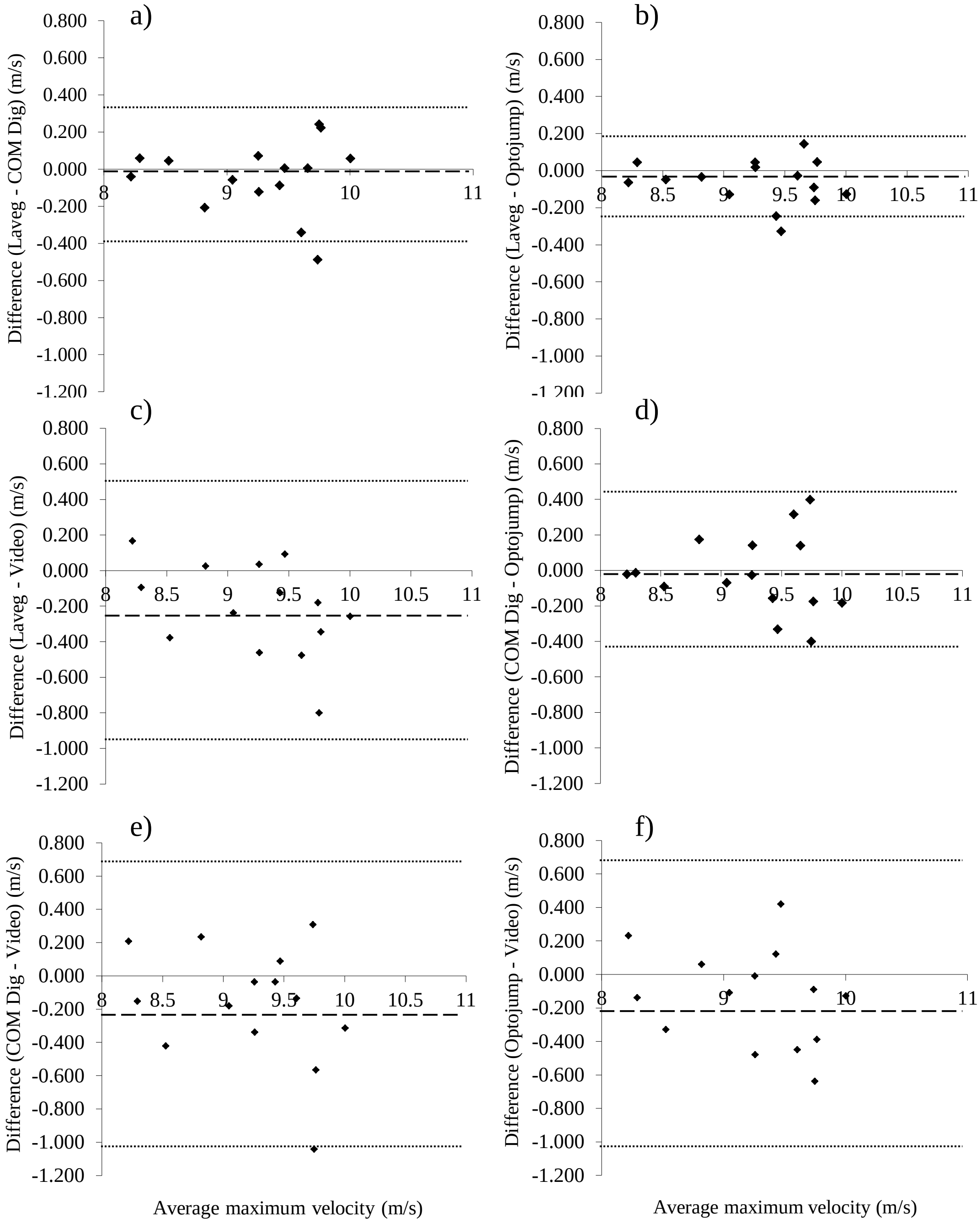


Figure 3-6 Bland-Altman plot illustrating systematic bias and 95% limits of agreement for each of the method comparisons for establishing maximum velocity. The mean value between the two methods is plotted on the x-axis, and the difference between the two methods (detail on the y-axis) is plotted on the y-axis. The wide dashed line represents the systematic bias, and the narrow dashed lines represent the +95% and -95% confidence intervals.

The data collection methods mentioned thus far are used to establish the general kinematic variables inherent to elite maximal velocity sprinting. However to further understand the technique associated with maximal sprinting manual digitisation can be used to establish a full body COM profile along with joint angles and angular velocities. In order to confidently associate changes in kinematics with changes in horizontal velocity the reliability of this method must be established. This is particularly relevant for practioners working with elite athletes where small but practically important changes in technique and performance occur (Hopkins, 2004). Previously intraclass correlations (ICC) have been calculated as estimates of interrater (between-rater) and intrarater (within-rater) reliability (Eliasziw, Young, Woodbury, & Fryday-Field, 1994). However the ICC value is a score from 0-1 and is not an easy measure to decipher for a scientist and coach. Furthermore it is difficult to compare ICC values between studies as it is generally known that the ICC based on several measurements will be greater than the ICC from a single measurement (Fleiss, 1999). A more appropriate measure is to use the mean difference which then gives a measure of error in the relevant units.

The results are presented in Table 3-4. The typical error (TE) is an indication of the noise or uncertainty in the variable. Thus for a change in a variable to be deemed meaningful it must exceed the TE (Hopkins, 2004). The mean TE for the distance variables is 0.002m, for speed variables 0.01m/s, for angle variables 0.51° and angular velocity variables 7.97°/s. These are the smallest changes that must be observed in a variable before the difference can be deemed worthwhile and will be applied throughout the thesis. Furthermore the small variability between the different variables within each category implies that the same TE can be applied across different variables within each category. The high reliability of manual digitisation means it is sufficient for each trial in the thesis to be digitised once rather than using an average of multiple trials. In order to establish the interrater reliability the same kinematic variables were calculated for Researcher B and a paired t-test was used to establish whether there was a significant difference in variables between researchers. The paired t-test indicated a p value of 0.622 indicating no significant difference, and thus repeatability across researchers. However only one researcher will be used for all digitisations throughout the thesis.

Table 3-4 Intrarater reliability represented as mean difference for the key kinematic variables of sprinting. Typical error (TE) and limits of agreement (LOA) are presented.

Variable	Mean difference	±SD	TE (±SD/√2)	LOA (±SD*1.96)
Distance				
Height of COM (m)	0.005	0.004	0.002	0.008
Touchdown distance (m)	0.004	0.003	0.002	0.007
Stance distance (m)	0.004	0.003	0.002	0.007
Speed				
Horizontal velocity of COM (m/s)	0.03	0.02	0.01	0.07
Vertical velocity of COM (m/s)	0.05	0.02	0.01	0.04
Angle				
Hip angle at TD (°)	0.52	0.39	0.28	0.77
Knee angle at TD (°)	1.14	0.59	0.41	1.16
Knee angle MKF (°)	1.44	1.12	0.79	2.19
Hip angle at TO (°)	0.66	0.53	0.37	1.04
Knee angle at TO (°)	1.51	0.97	0.69	1.92
Angular velocity				
Average hip extension velocity (stance) (°/s)	15.74	14.36	10.15	28.15
Average hip flexion velocity (recovery) (°/s)	13.44	9.64	6.81	18.88
Average knee extension velocity (stance) (°/s)	15.91	9.82	6.94	19.24

3.4 Conclusion

When working within an applied environment the equipment and procedures available to a biomechanist are restricted. Therefore the typical equipment used must be tested to establish both its limitations, but also its advantages for use within an applied environment. Often there is more than one analysis tool available and therefore a biomechanist must select the most appropriate tool based on its advantages and disadvantages.

Video cameras are predominantly used as a feedback tool for coaches and athletes to make subjective observations about performance; however they can also be used by a biomechanist to provide objective data. If high-speed video is used (300fps), frames can be counted to provide a measure of GCT and FT to an accuracy of 0.003s. As mentioned the use of additional track markings at 1m intervals means a panning video camera can be used to estimate athletes step lengths over the prescribed distance.

However each of these variables can also be determined using the Optojump system, which is deemed favourable due to the reduction in post-analysis time. The results of the current study indicate the mean error between cameras and Optojump to be 0.001s for FT and GCT and 2cm for SL, which equates to a mean percentage difference of less than 2% which is deemed an acceptable level for comparing between the two measurement techniques. Furthermore the Optojump system is advantageous as it provides additional gait analysis data within the same analysis (e.g. step lengths); whereas using the video analysis would necessitate additional track markings to establish SL. The limitations associated with the Optojump system are the set-up time, need for external power, the inability for it to be used in wet weather conditions and the prevention of its use within a competition environment. Although high-speed cameras are permitted within a competition the high frame rate necessitates a large amount of light which is often problematic when indoors. The wide use of Laveg within the applied sports environment has led to this being deemed the gold standard measure, and its ability to provide immediate feedback is a desirable feature to a coach and biomechanist. However due to the problems discussed above Laveg is not always available, and thus other techniques must be employed to establish horizontal velocity. As mentioned manual digitisation can be used, however this is time consuming as it requires a full 18-point digitisation along with post-processing of inertial parameters to establish a velocity of the COM. The greatest level of agreement was reported between Laveg and Optojump; however an acceptable level of agreement was also obtained between Laveg and manual digitisation. The TE of key kinematic variables provides a value of the smallest worthwhile change in a variable before a true difference can be inferred. These values will be used throughout the thesis to determine the true kinematic differences observed between elite and sub-elite athletes in Chapter 4, along with establishing the true levels of specificity in Chapter 6.

3.5 Chapter summary

This chapter aimed to establish the reliability and validity of different measurement techniques available to calculate the kinematic variables of maximal velocity sprinting within the applied environment. The results indicated a high level of agreement between methods, meaning techniques can be used interchangeably and can be based on the requirements of the environment. This clearly answers research question i - *what are the most appropriate measures for analysing the kinematics of maximal velocity sprinting and the associated training methods?* The identification of maximal velocity is favoured from the Laveg due to the high frequency of the measure and the lack of post-processing time, and high-speed cameras are preferential due to the ability to obtain a full COM profile alongside the key performance variables of sprint velocity. The findings of this chapter will be used to address research question ii - *which kinematic variables are associated with elite levels of maximal velocity sprinting?* The typical error associated with each the measurement techniques and from manual digitising has been established to identify what is a true indicator of elite levels of maximal sprinting.

CHAPTER 4 – DEVELOPMENT OF KINEMATIC TECHNICAL MODEL OF MAXIMAL VELOCITY SPRINTING

4.1 Introduction

Technique analysis is the term given to an analytical method that is used to understand the way in which sports skills are performed, and through this understanding provide the basis for improved performance (Lees, 2002). It is only in the past half century that technique analysis has begun to incorporate scientific principles within coaching practice. As analysis methods have been developed, coinciding with the development of new technologies, it is now possible to measure both the kinematic and kinetic variables associated with elite sprinting performance. This approach is known as quantitative analysis. However quantitative analysis poses the problem that multiple variables are obtained, and thus they must be processed in a way that reflects the essential considerations of the technique (Lees, 2002). Furthermore there is the danger that this will increase the number of less than meaningful observations reported in the scientific literature (Chow & Knudson, 2011). This necessitates narrowing down the available variables to those that specifically relate to technique as discussed in Chapter 2.

Commonly the most widely used justification for the inclusion of a variable in quantitative analysis is by reference to previous research and coaching articles. For example the majority of elite maximal velocity sprinting literature refers to ground contact time – which warrants its inclusion in further research. Yet this approach should not be used in isolation as it is possible previous research failed to identify, or was unable to measure, additional key critical determinants of performance. In a limited research area such as the technique of elite maximal velocity sprinting it may be proposed that future authors use a ‘logical’ basis for the selection of variables (Lees, 1999). This is the inclusion of variables that are deemed to have some prior importance to the movement. The biomechanical principles of movement provide a rational basis for selecting technique variables. One such method of expressing the relationship between variables this is a deterministic model as outlined in Chapter 2. A limitation of a deterministic model acknowledged by Lees (2002) is that the variables identified are performance outcome variables. For many complex skills the performance is clearly related to aspects of technique that cannot be accounted for within the deterministic model. This is particularly relevant in sprinting as whilst the horizontal velocity is determined by step length and step frequency, it fails to take into account how the technique (such as joint angles and angular velocities) impact on these performance variables. Recently authors have acknowledged that the movement patterns in sprint running are determined by segment interactions (or joint couplings), yet an incomplete understanding of these couplings currently exists.

An understanding of the joint and limb kinematic profiles for the entirety of a sprint stride is fundamental in gaining a full insight into the technique paramount to elite levels of performance. The notion that movement patterns used in sprint running may be determined by a combination of joint couplings as opposed to isolated joints was first advocated by Hunter et al. (2004c), but limited understanding of the joint couplings in sprint running currently exists. An insight into the lower limb joint coupling motions of sprint running would enhance understanding of the task-specific movement patterns associated with high level sprint performance. Gittoes and Wilson (2010) investigated coordination of the maximal phase of sprint running, however the average horizontal velocity was 8.57m/s which is not comparable to the elite sample in this thesis. Furthermore the authors failed to investigate the role of variability with respect to skill at maximal velocity sprinting.

The process used to develop the technical model of elite maximal sprinting is modelled in Figure 4-1. An a-priori approach was adopted based on the biomechanical principles associated with maximal velocity sprinting as discussed in Chapter 2. The analysis will begin with a description of the performance variables associated with maximal sprinting. Following this the joint angles and angular velocities throughout a gait cycle will be discussed, followed by a more detailed analysis at the key positions of touchdown, mid-stance and toe-off. The analysis will progress to discuss the interjoint coordination through means of lower limb joint couplings.

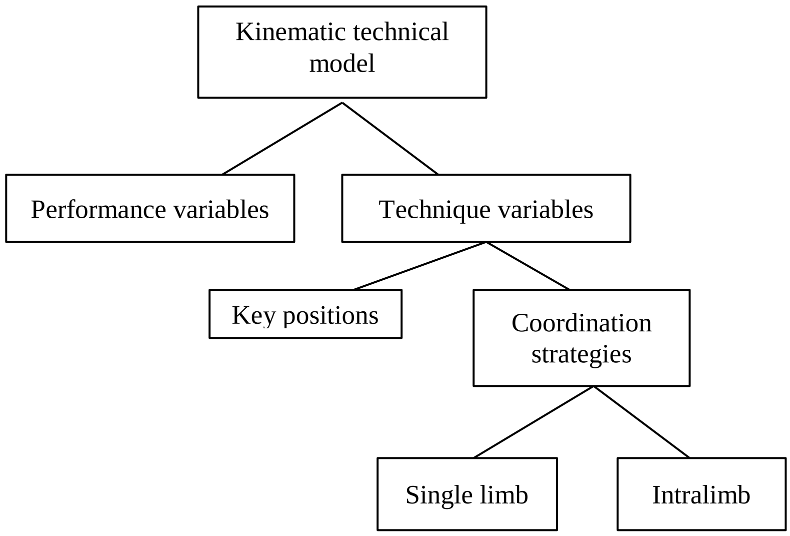


Figure 4-1 Approach for the development of kinematic technical model of maximal velocity sprinting

4.2 Methods

Data was obtained from a sample of 20 international and national level male sprinters during the 2011-2012 competitive season (mean 100m personal best times 9.85 ± 0.12s). The sample included previous 100m world record holders and five of the finalists from the 100m final at the London 2012 Olympics. Data were collected from UK-based competitions during the summer season during both 100m and 200m races.

An unobtrusive manual video analysis approach (as described and validated in Chapter 2) was used, so that high performance data could be collected for international sprinters with no interference from the experimenter. Data was collected during a competitive race and thus only one trial was achievable for each athlete. A high-speed video camera (CASIO Exilim F1) operating at 300fps was located on the infield of the running track. The camera was positioned perpendicular to the running lane, 15m from the centre of Lane 4 and 65m from the 100m start line. This position was selected as elite athletes typically reach their maximum velocity between 60-80m (Krzysztof & Mero, 2013). Lane 4 was selected as the priority lane as due to seeding the fastest athletes are allocated the centre lanes. This provided a subsequent field of view of Lanes 2 – 6 to analyse four complete ground contacts and subsequently allow analysis of a full stance and swing phase for both limbs. Either before or after the competition a 2-dimensional calibration frame of dimensions 1.06 x1.20m was used to calibrate the entire field of view.

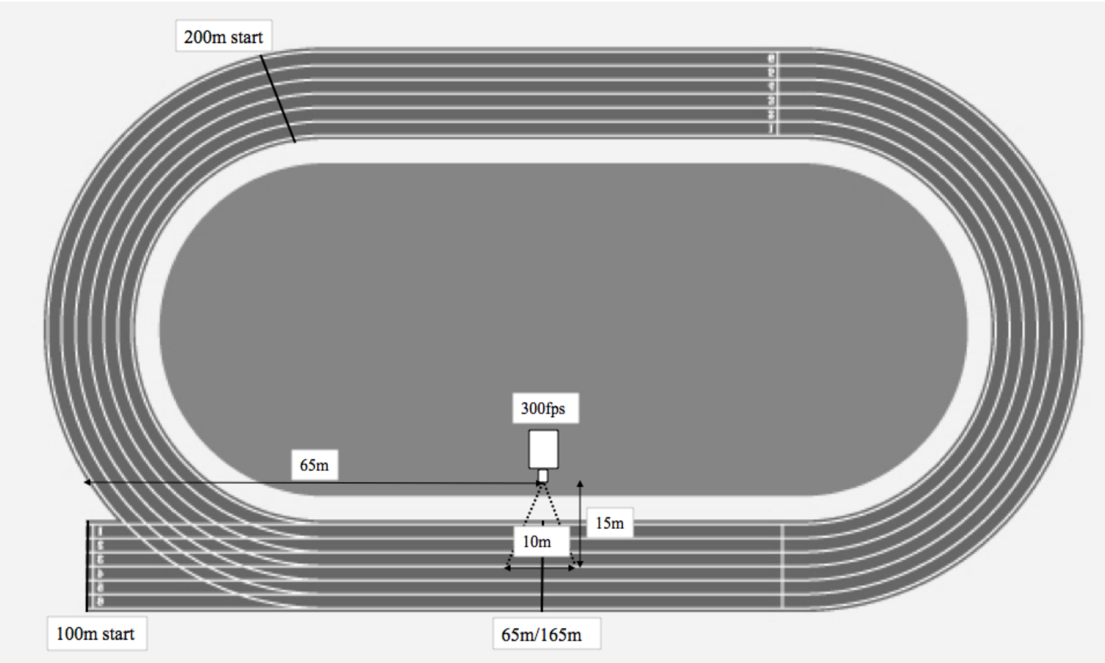


Figure 4-2 Experimental set-up for collection of kinematic data during competition

The raw videos were imported into the digitising software (Quintic Biomechanics Version 21). An 18-point, 14-segment model was employed, digitised points were: vertex, C7, greater tuberosity of humorous, elbow, wrist, third metacarpal, greater trochanter of femur, lateral epicondyle, lateral malleolus, 5th metatarsal joint. The first digitisation frame was identified as the frame number occurring 30 frames prior to the first key event (either the touchdown or toe-off of a stride dependent on which occurred first). The subsequent frames were then digitised at 300fps until two complete strides had been digitised. Digitisation continued until 30 frames after the last key event (touchdown or toe-off dependent on which occurred last). The horizontal and vertical scale factors calculated from the calibration frame were applied to scale the raw digitised coordinates and obtain absolute displacement-time histories. Once digitisation was complete the raw coordinates were exported to an excel file and all subsequent analysis took place using a customised Excel spreadsheet (Microsoft Version 14.4.2).

Data were filtered using a fourth-order low-pass Butterworth digital filter (Winter, 1990). Cut-off frequencies were determined using a residual analysis approach in order to obtain the most appropriate degree of minimal signal distortion and maximal noise removal. Residual analysis was performed individually for each of the 18 anatomical points and an average cut-off frequency of 11Hz was utilised. All filtered joint displacement data were combined with segmental inertial data (de Leva, 1996) in order to create a whole body 14-segment model (head, trunk, upper arms, lower arms, hands, thighs, shanks, feet). Displacement values were differentiated using second central difference equations (Miller & Nelson, 1973) to determine a COM velocity.

The key kinematic variables to maximal velocity sprinting as identified from the deterministic model (Figure 2-8) and based on biomechanical principles were extracted from the raw coordinate data through the use of a bespoke spreadsheet developed in Excel. For ease of comparison each stride was split into a 'swing' phase which represented TO of one leg to the TD of the same leg, and a 'stance' phase which represented the TD of one leg until the TO of that same leg (Figure 4-4).

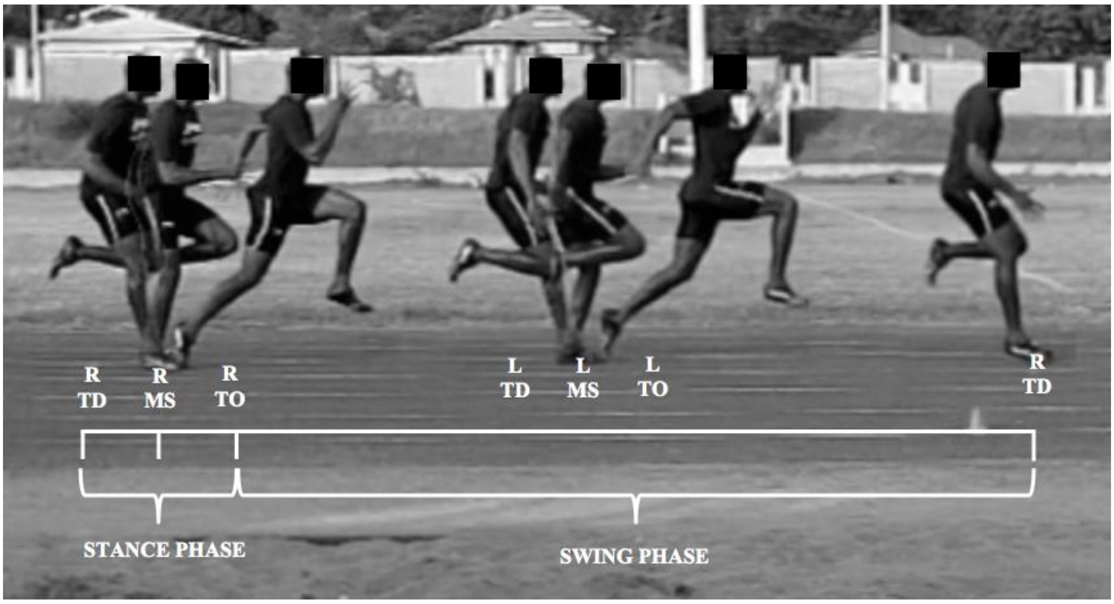


Figure 4-3 Gait analysis split into stance and swing phases (right leg shown)

Touchdown (TD) was defined as the first frame where the foot definitely makes contact with the ground, and toe-off (TO) was the frame where the foot is definitely clear of the ground. Mid-stance (MS) was defined at the point where the horizontal coordinate of the centre of mass is directly in line with the horizontal coordinate of the foot on the ground. Mid-stance was identified as a critical time point as it represents the transition from braking to propulsive horizontal forces. As data was collected within competition it was only possible to get one trial per athlete. Therefore to reduce error two stance phases (right and left leg) and two swing phases (right and left leg) were averaged to give an averaged swing and stance phase for each athlete. Subsequently from this point on the limbs will be referred to as the 'stance limb' and the 'swing limb'. Joint angles at these specific events were calculated using the definitions specified in Table 4-1, along with the peak and average joint angular velocities. The COM height (and the relative change in height over a stride) was determined using the y-coordinate of the COM. Stance distance and flight distance were defined as the horizontal distance travelled by the COM during these respective phases. Touchdown and toe-off distance was calculated as the difference between the horizontal coordinate of the COM and the horizontal coordinate of the 5^{th} metatarsal. Maximum hip flexion (MHF) was defined as the minimum hip angle (i.e. maximum flexion) of the swing leg during the swing phase.

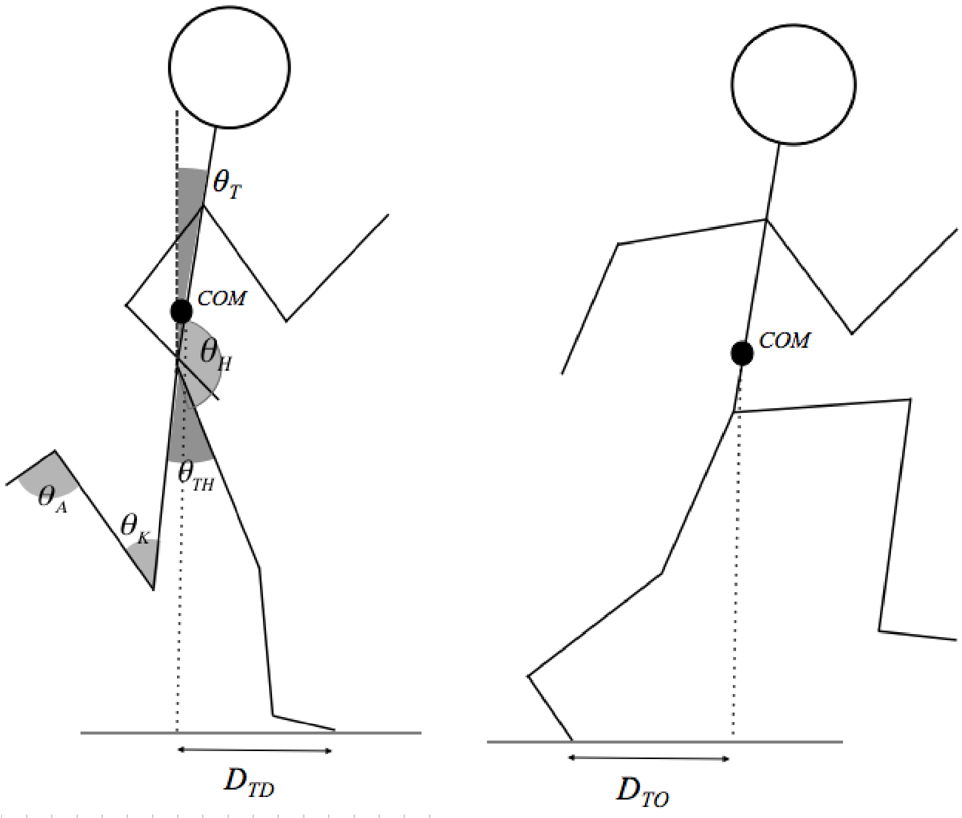


Figure 4-4 Description of angle definitions used throughout the analysis, where *COM* is the centre of mass, θ_H is hip angle, θ_K is knee angle, θ_A is ankle angle, θ_{TH} is thigh angle, θ_T is trunk angle, D_{TD} is the touchdown distance and D_{TO} is the toe-off distance

Table 4-1 The angle definitions used throughout the thesis and the convention used to denote positive and negative values

Variable	Calculation	Notes
Hip angle *(θ_H)*	The internal angle between a vertical line passing through the COM and the line joining the hip joint centre and the knee joint centre	A value 0-180° indicates the thigh is in front of the vertical (line through the COM) whereas an angle 180-360° indicates the thigh is behind the vertical
Knee angle *(θ_K)*	The internal angle between a line joining the hip joint centre and the knee joint centre to the ankle joint centre	0° indicates full flexion and 180° indicates full extension. >180° indicates hyperextension
Ankle angle *(θ_A)*	The internal angle between a line joining the knee joint centre and the ankle joint centre and the ankle joint centre to the 5th metatarsal	0-90° indicates plantarflexion, 90-180° indicates dorsiflexion
Thigh angle *(θ_{TH})*	The angle formed between the two thighs at the point of touchdown	A positive value indicates the swing thigh is in front of the stance thigh, a negative value indicates the stance thigh is ahead of the swing thigh
Trunk angle *(θ_T)*	The angle formed between a vertical line passing through the COM and the line joining the hip joint centre and C7	A positive value indicates forward inclination, a negative value is backward inclination
Touchdown distance (D_{TD})	Distance between the x-coordinate of the 5th metatarsal and the x-coordinate of the COM at the point of touchdown	
Toe-off distance (D_{TO})	Distance between the x-coordinate of the 5th metatarsal and the x-coordinate of the COM at the point of toe-off	
Centre of mass *(COM)*	Calculated from a 14-segment model based on segmental inertias	

In order to establish the critical determinants to attaining sprint velocities >10.0m/s the sample was split into two sub-groups (see Table 4-2). The elite group (n=10) was defined as athletes with an average horizontal velocity over a digitised stride >10.0m/s (thus coinciding with the definition of elite as defined in the introduction of the thesis). The sub-elite group (n=10) was defined as athletes who attained an average horizontal velocity over a digitised stride <10.0m/s. The TE in maximal velocity associated with manual digitising was 0.01m/s and therefore it is concluded these groups truly represent elite and sub-elite levels. These sub-groups typify international and national level sprinters respectively.

Table 4-2 Average horizontal velocities (m/s) over a digitised stride of the 'elite' and 'sub-elite' samples

	Elite (>10.0m/s)	Sub-elite (<10.0m/s)
	12.25	9.99
	11.91	9.92
	10.93	9.95
	10.69	9.97
	10.64	9.55
	10.50	9.66
	10.23	9.67
	10.90	9.13
	10.85	8.86
	10.15	8.81
Mean	10.91	9.55
±SD	0.68	0.46

Data were tested for normality using the Shapiro-Wilk test. A non-significant result indicated the data was distributed normally and therefore a parametric test could be used to test for significant differences. Differences between the elite and sub-elite samples for the joint angles at TD, MS and TO and the peak and average angular velocities during stance and swing were examined using independent samples t-test. Homogeneity of variance was tested using Levene's test for equality of variances and a non-significant result indicated the two samples were obtained from populations of equal variances. The relationship between the independent variables stated above and horizontal velocity were assessed using a Pearson's product moment correlation, classified as weak (0.10-0.29), moderate (0.30-0.49) and strong (>0.50) (Cohen, 1988). Statistical significance was set at $p<0.05$. Data were analysed using the statistical package SPSS (Version 20.0).

Many techniques exist to quantify interjoint coordination. Phase planes were used to assess the angle of a joint relative to its angular velocity. The joint angle and angular velocity were normalised to the maximum and minimum of the athlete-specific data set according to the procedure presented by Hamill et al. (1999). Normalisation of each oscillator facilitates comparisons between limbs for interlimb coordination analyses as it adjusts for amplitude differences in the range of the motion and centres the phase plot about an origin. The joint angle and angular velocity traces were interpolated to 101 data points and represented as a percentage of the gait cycle. Each phase plot was determined in raw units with angular displacement on the abscissa and its first derivative, angular velocity, on the ordinate (Scholz, 1990). Intralimb coordination was quantified using continuous relative phase (CRP). The CRP approach has been utilised in previous studies of running mechanics due to its ability to obtain a continuous measuring of coupling throughout a gait cycle (Hamill et al., 1999). The CRP was calculated as per the methods of Sides and Wilson (2012). Phase angles were calculated from the normalised phase plot using the arctangent function of the normalised position and velocity time series (Kurz & Stergiou, 2002). The CRP was calculated for two intralimb couplings of interest: (i) hip flexion/extension–knee flexion/extension (HK) and (ii) knee flexion/extension–ankle dorsi/plantar flexion (KA). The CRP time histories for the sagittal plane HK and KA joint couplings were determined by quantifying the difference between the phase angle of the distal and proximal joint at each time point. A CRP of 0° corresponds to in-phase coupling, meaning that the phase angles for the two motions are identical and are rotating in the sample direction. A CRP of 180° indicates an anti-phase coupling (i.e. the joints are rotating in opposite directions). Mean ensemble CRP values were used to compare the difference in coordination of joint couplings between the elite and sub-elite samples. Coordination variability (CRPv) was calculated as the standard deviation at each time point and was averaged across athletes. The group mean CRP and CRPv were calculated for the TD, MS and TO time points of the gait cycle, along with an average for the stance, swing and entire gait cycle. In order to establish whether variability is advantageous in maximal velocity sprinting the CRPv between the elite and sub-elite samples were compared using an independent samples t-test.

4.3 Results

The average horizontal velocity for the sample was 10.23m/s. It has been shown that any velocity between 95 and 100% of the athlete's absolute maximum employs identical mechanics (Seagrave et al., 2009). As data was collected during competition it can be assumed that athlete's were performing to the maximum of their ability and thus should represent their true maximum. The deterministic model (Figure 2-8) indicates all the independent variables that define maximal horizontal velocity. As per the methods of Guimaraes and Hay (1985) all independent variables were correlated with the average horizontal velocity achieved over the analysed stride for each of the 20 athletes. The mean and standard deviation for the general kinematic variables (the upper levels of the deterministic model), along with the correlations to horizontal velocity are presented in Table 4-3. All variables were significantly correlated with horizontal velocity ($p<0.05$). Step length, step frequency, flight distance and stance distance all displayed positive correlations indicating an increase in these variables is associated with an increase in horizontal velocity. Stance and flight time displayed a negative correlation indicating shorter times are associated with an increase in horizontal velocity. The coefficient of determination was calculated to establish the predictive ability of each of these variables to horizontal velocity. Flight distance and stance distance were the strongest predictors of horizontal velocity, predicting 43% and 42% of the variance respectively. Flight time had the lowest correlation to horizontal velocity which coincides with existing research that flight time does not differ with sprint velocity (Mann, 2010).

Table 4-3 Mean ±SD of general kinematic variables and their associated correlations to maximal horizontal velocity (* indicates $p<0.05$)

Independent variable	Mean (±SD)	Correlation with horizontal velocity (r)	Coefficient of determination (R^2)
Horizontal velocity (m/s)	10.23 (0.89)		
Step length (m)	2.30 (0.16)	0.600*	0.360
Step frequency (Hz)	4.50 (0.32)	0.501*	0.250
Flight distance (m)	3.62 (0.30)	0.652*	0.425
Stance distance (m)	1.00 (0.07)	0.644*	0.415
Ground contact time (s)	0.099 (0.007)	-0.590*	0.348
Flight time (s)	0.347 (0.28)	-0.410*	0.168

Whilst reporting angular and angular velocity data at key positions provides an easy measure by which to analyse technique it fails to acknowledge the movement as a whole, i.e. the path of a joint throughout the gait cycle. Interestingly very little research reports joint angles for the entirety of the stride, possibly due to the time consuming nature of obtaining such information. Typically data in the literature is normalised to a percentage of the gait cycle, however a gait cycle is often defined as the time from TD of one limb to TD to the contralateral limb. This negates the full swing cycle of the swing leg, and subsequently a gait cycle in the current study is defined as the point of TD of one limb till the point of TD of that same limb (Figure 4-3). The lower limb joint angle and angular velocity cycles for the full stance and swing phase of one limb are presented in Figure 4-5 and Figure 4-6 respectively. The points of TD, MS and TO are represented as vertical lines on the graphs. In addition the point of TD of the opposite limb is marked to facilitate comparisons with existing literature.

From TD through to MS both the knee and ankle flex whilst the hip extends (Figure 4-5). The knee and hip reach maximum flexion after MS, and then extend approaching toe-off. Interestingly just prior to TO the knee flexes slightly, so maximum extension is actually achieved just prior to TO. Furthermore neither the hip nor ankle are in a maximally extended position at this point. The hip continues to extend for a brief period after TO to a point of maximum extension of 194°. Following TO the ankle continues to extend slightly to a maximum plantarflexed position of 141°. The graph then plateaus indicating the ankle joint does not fluctuate much in the early stages of swing. Following maximum hip extension the hip flexes at the same rate as the knee, and the point of maximum hip flexion (98°) (i.e. high knee position) is reached at 70% of the gait cycle. Following this the hip extends to a point of 128° by TD. In the second half of the gait cycle the ankle then flexes to a position of 97° and then fluctuates by approximately 10° around this position approaching TD. At the point of TD the hip has an extension velocity which continues to accelerate to a point of maximal extension velocity at 50% of the stance phase (past the point of MS) (Figure 4-6). At TD the knee and ankle have similar flexion velocities which decelerate at the same rate until zero angular velocity is reached just following the point of MS. Following MS the knee reaches a maximum knee extension velocity (during stance) of 200°/s whilst the ankle extends rapidly to a maximal extension velocity of 1100°/s. All three joints then decelerate approaching TO, and the knee begins to flex just prior to TO at a velocity of 300°/s. The hip joint switches from extension to flexion just following TO which is evident when the angular velocity is 0°/s. The hip continues to increase in flexion velocity to a maximum flexion velocity of -800°/s at 55% of the gait cycle. Following this the hip decelerates to the point of maximum hip flexion at 75% of the gait cycle, and then extends at a constant velocity of 400°/s until TD. The knee reaches a maximum flexion velocity of -1000°/s much earlier in the swing phase, and then decelerates to the point of maximum knee flexion at 55% of the gait cycle. The knee then undergoes a very rapid extension to a peak of 1200°/s, at which point the knee decelerates and actually has a slight flexion velocity by the point of TD. The angular velocity of the ankle fluctuates throughout the swing phase between -400°/s and 200°/s, and also has a dorsiflexion velocity at the point of TD.

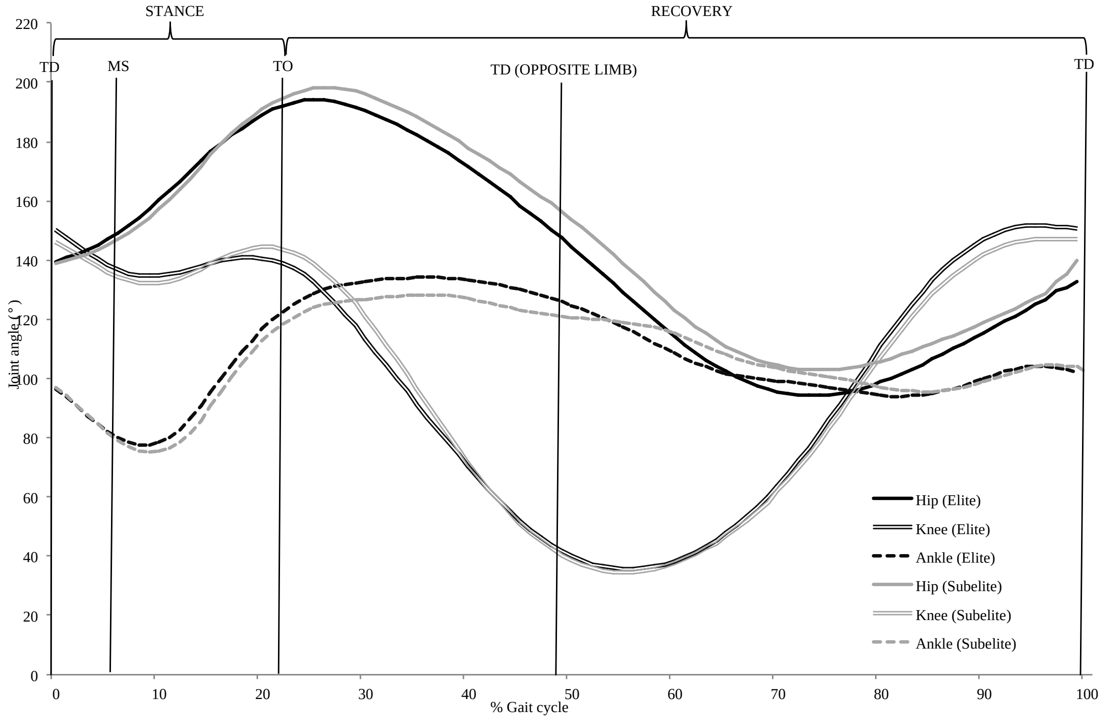


Figure 4-5 Joint angle profile of a full gait cycle of the hip, knee and ankle joints for elite (black lines) and sub-elite (grey lines) athletes

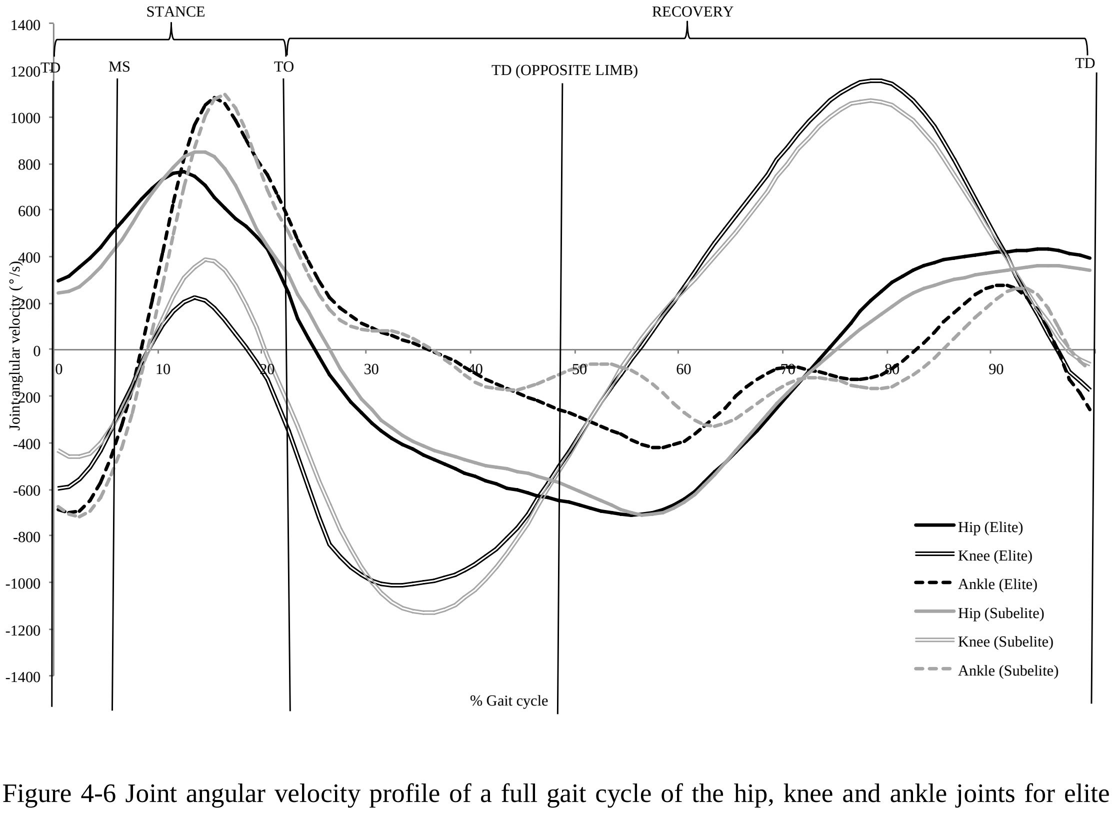
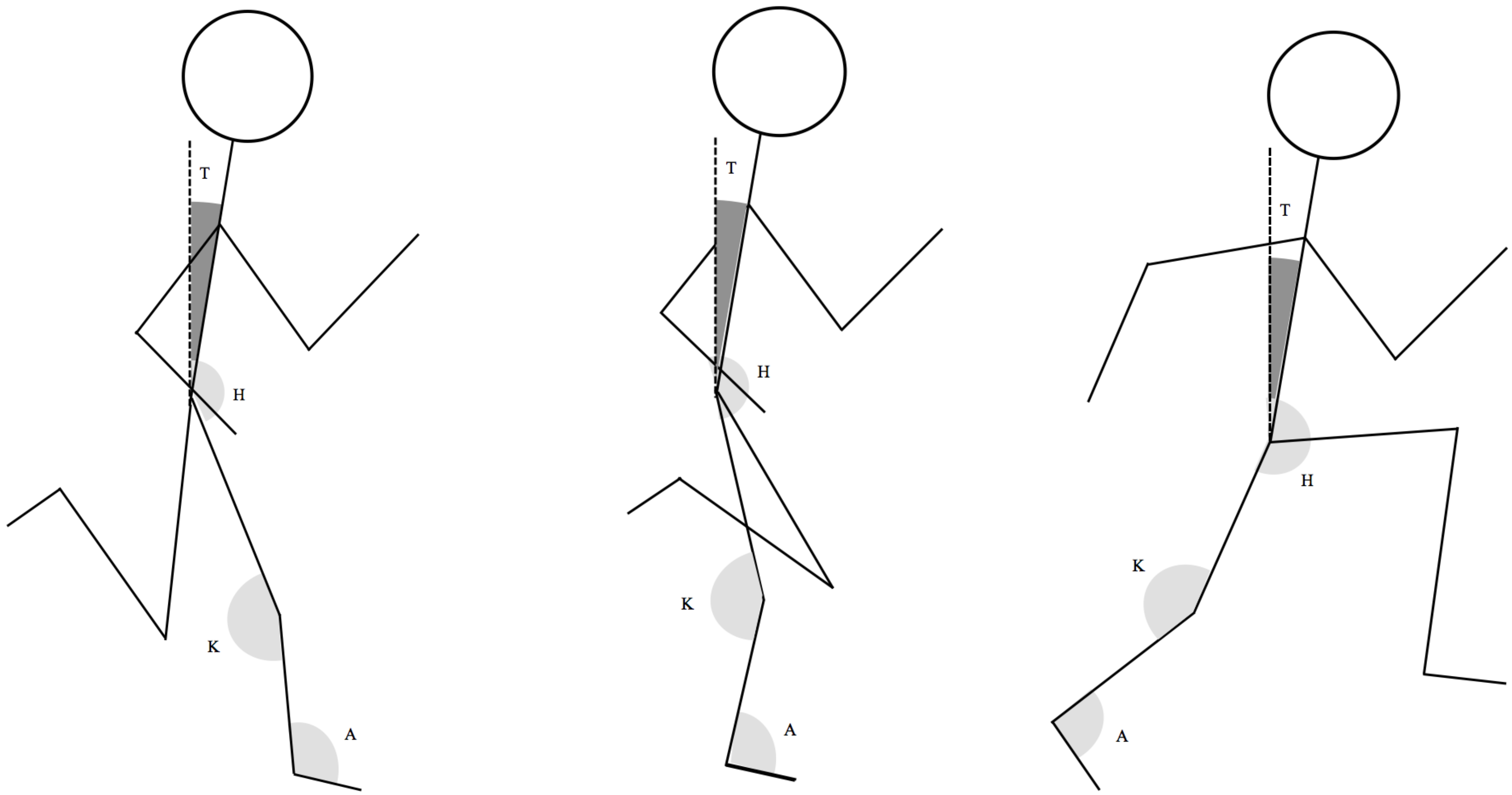


Figure 4-6 Joint angular velocity profile of a full gait cycle of the hip, knee and ankle joints for elite (black lines) and sub-elite (grey lines) athletes

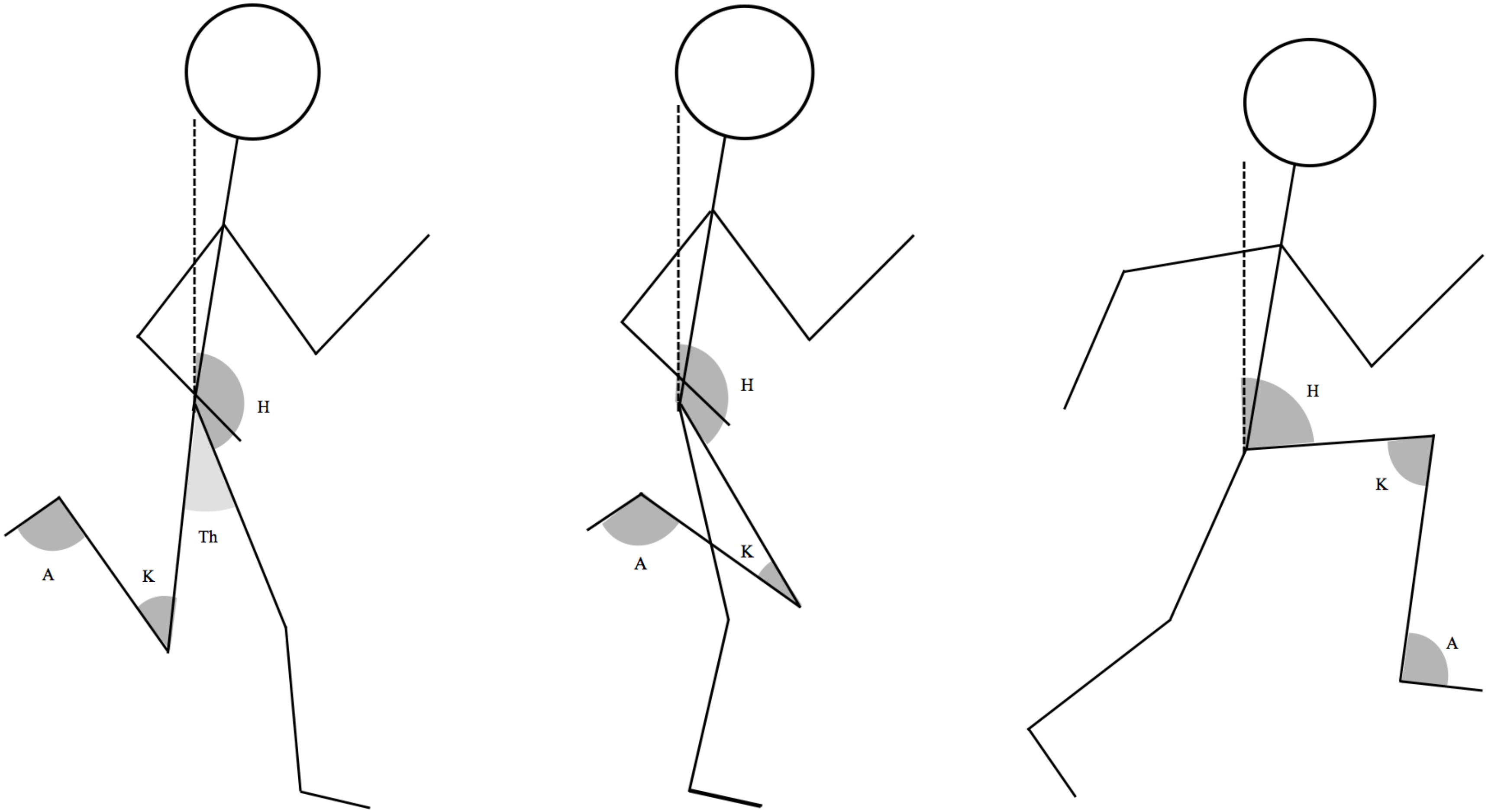
Figure 4-7 indicates the stance leg joint angles of the elite and sub-elite samples at the key positions of TD, MS and TO. At TD there was no significant difference between the elite and sub-elite sample for either the trunk, hip, knee or ankle angle. At MS elite athletes had significantly less flexion of the knee and ankle joints compared to the sub-elite sample indicating a more rigid stance limb. At the point of TO there were no significant differences in joint angles between the elite and sub-elite samples. A Pearson correlation between each of the joint angles and the average horizontal velocity of the stride indicated only the ankle angle at MS had a strong correlation to maximal velocity. A number of variables had a moderate correlation to maximal horizontal velocity, which commonly occurred in the MS and TO positions.

A novel approach of this thesis is the inclusion of the joint angles of the swing leg in the kinematic analysis (Figure 4-8). The hip angle of the swing leg at TD had a strong correlation to maximal velocity and was significantly smaller (more flexion) in elite athletes in comparison to sub-elite athletes. Similarly elite athletes had a significantly smaller thigh angle (angle formed between the two thighs) of 14° in comparison to the sub-elite sample (27°), which was also strongly correlated to maximal velocity. There was no difference in the knee and ankle angles of the swing leg at this time point. At the point of both MS and TO the hip angle of the swing leg was still significantly less in elite athletes indicating the swing leg is further forward at this point in the gait cycle, although the magnitude of difference between the samples was less than at the point of TD (28°). The knee and ankle angles of the swing leg displayed a weak correlation to horizontal velocity throughout the swing phase.



		Touchdown			Mid-stance			Toe-off		
		Elite	Sub-elite	Correlation	Elite	Sub-elite	Correlation	Elite	Sub-elite	Correlation
	Trunk (T)	14 (4)	12 (4)	0.339	13 (4)	12 (3)	0.302	11 (3)	7 (3)	0.491
Stance leg	Hip (H)	147 (6)	145 (8)	0.215	160 (5)	157 (4)	0.179	198 (6)	193 (8)	0.349
	Knee (K)	151 (4)	148 (4)	0.147	141 (5)*	135 (3)	0.437	142 (6)	145 (7)	0.421
	Ankle (A)	101 (4)	100 (3)	0.085	84 (4)*^	79 (2)	0.555	116 (6)	118 (5)	0.299

Figure 4-7 Mean (±SD) lower limb joint angles of the stance leg at key events (all angles in degrees) *indicates significant difference between elite and sub-elite. ^ indicates strong correlation (r = >0.5) to maximum horizontal velocity. Figure illustrates joint angle definitions (not to scale).



		Touchdown			Mid-stance			Toe-off		
		Elite	Sub-elite	Correlation	Elite	Sub-elite	Correlation	Elite	Sub-elite	Correlation
Swing leg	Hip	163 (6)*^	135 (3)	0.689	141 (5)^	133 (7)	0.572	107 (6)*^	102 (5)	0.512
	Knee	44 (5)	41 (7)	0.165	36 (5)	32 (6)	0.152	73 (7)	65 (7)	0.292
	Ankle	123 (7)	123 (12)	0.013	116 (8)	120 (12)	0.193	96 (5)	98 (6)	0.380
	Thigh angle (Th)	14 (7)*^	27 (8)	0.597						

Figure 4-8 Mean (±SD) lower limb joint angles of the swing leg at key events (all angles in degrees) *indicates significant difference between elite and sub-elite. ^ indicates strong correlation (r = >0.5) to maximum horizontal velocity. Figure illustrates joint angle definitions (not to scale).

The maximum and average angular velocities of the hip, knee and ankle joints for the stance phase are presented in Table 4-4. The maximum hip velocity was slightly greater in the sub-elite group (873°/s) in comparison to the elite sample (805°/s). However when averaged for the entirety of the stride the elite sample had a higher average velocity, though this was not significantly different. There was no significant difference in the maximum knee flexion velocity between the elite and sub-elite samples. However the sub-elite athletes had a maximum knee extension velocity almost twice that of the elite sample which was significantly different. Furthermore the maximum knee extension velocity displayed a strong correlation to maximum velocity. Yet when averaged for the entirety of the stance phase the elite sample had a higher average knee angular velocity (-122°/s), with a negative value indicating the average velocity was a flexion velocity. There was no significant difference between the maximum and average ankle velocities between the two groups.

Table 4-4 Mean (±SD) average and maximum joint angular velocities (°/s) for the stance phase *indicates significant difference between elite and sub-elite. ^ indicates strong correlation (r = >0.5) to maximum horizontal velocity

STANCE (°/s)	Max		Average	
	Elite	Sub-elite	Elite	Sub-elite
Hip flexion velocity	-232 (98)	-236 (135)	571 (59)	558 (56)
Hip extension velocity	805 (88)	873 (84)		
Knee flexion velocity	-540 (111)	-499 (204)	-122 (68)^	-29 (64)
Knee extension velocity	251 (151)*^	450 (152)		
Ankle dorsiflexion velocity	-733 (83)	-744 (93)	174 (53)	175 (58)
Ankle plantarflexion velocity	1182 (67)	1244 (143)		

Surprisingly the joint angular velocities in the swing phase have received little attention in the past. The maximum and average angular velocities of the hip, knee and ankle joints during the swing phase are presented in Table 4-5. The mean hip velocity during swing was -158°/s for the elite sample and -167°/s for the sub-elite sample which was not significantly different. The average value is low due to the averaging of flexion (negative) and extension (positive) velocities. Similarly the average knee angular velocity in swing is low but the maximum extension and flexion velocities both exceed 1000°/s in both the elite and sub-elite samples, with no significant differences between the two. The only significant difference observed between the samples was the maximum ankle plantar flexion velocity which was higher in elite athletes (857°/s) and was strongly correlated to horizontal velocity. However as with the angular data the lack of significant differences from a t-test may be a function of the small sample size. The smallest meaningful difference for angular velocities as calculated in Chapter 2 was 8°/s, and the majority of the differences between the elite and sub-elite samples exceed these value are therefore are potentially important.

Table 4-5 Mean (±SD) average and maximum joint angular velocities (°/s) for the swing phase *indicates significant difference between elite and sub-elite. ^ indicates strong correlation (r = >0.5) to maximum horizontal velocity

SWING (°/s)	Max		Average	
	Elite	Sub-elite	Elite	Sub-elite
Hip flexion velocity	-733 (97)	-770 (71)	-158 (31)	-167 (30)
Hip extension velocity	567 (76)	526 (83)		
Knee flexion velocity	-1086 (100)	-1149 (133)	21 (32)	1 (25)
Knee extension velocity	1195 (133)	1133 (74)		
Ankle dorsiflexion velocity	-571 (179)	-528 (107)	-44 (19)	-44 (17)
Ankle plantarflexion velocity	857 (110)*^	697 (131)		

An understanding of the associated movement patterns used in sprint running is fundamental in gaining a full insight into the technique developments required to enhance performance. Quantifying the lower limb joint coordination provides an insight into lower extremity joint coupling motions defining elite maximal velocity sprinting. Plotting adjacent joints on the same graph facilitates analysis of the coordinative strategies associated with sprinting and how joints move relative to each other. Where angle-angle plots are reported they are typically used as a form of qualitative analysis to identify differences between two limbs or two sub-groups. In the current study angle-angle plots will be used to observe qualitative differences between an elite (>10.0m/s) and sub-elite (<10.0m/s) sample.

The ensemble hip-knee coupling of an entire gait cycle for the elite and sub-elite groups is presented in Figure 4-9. Touchdown occurs on the right hand side of the plot and passes in an anti-clockwise direction. It should be noted that as time is not included in the plots no reference can be made to timings, nor to associated angular velocities using angle-angle plots. References can only be made to the movement of joints in relation to each other. At the point of TD there is no difference in hip angle between elite and sub-elite athletes, however sub-elite athletes display more knee flexion. The rate of change in hip and knee angle from TD to the point of maximum knee flexion (for the stance phase) is the same between elite and sub-elite athletes (indicated by parallel lines). The maximum knee flexion angle is greater (more flexion) in sub-elite athletes. As indicated in Figure 4-5 TO occurs prior to the point of maximum hip extension. Following maximum knee flexion the sub-elite group extend the knee more than the elite group, and thus the two plots crossover. Consequently it can be concluded that sub-elite athletes have a greater knee ROM during the stance phase compared to elite athletes. Sub-elite athletes have a greater degree of hip extension following TO (plot is higher on the y-axis) compared to elite athletes. In the early phases of swing the coordinative strategies between elite and sub-elite athletes are the same as the hip and knee angles flex at the same rate (parallel lines), although the absolute degree of hip flexion is greater in elite athletes. The degree of maximum knee flexion (for the swing phase) is similar between the two sub-groups. The crossover of the plots indicates differences in the hip angle, with elite athletes reaching a smaller minimum hip angle (flexion) in comparison to sub-elite athletes. However as with the early swing phase the rate of change of the two joint angles is similar between both elite and sub-elite athletes. It can be concluded that the main difference between the sub-groups with respect to the HK coupling is the difference in the hip angle magnitude. The ROM is similar between the two groups (height of the plot), however throughout the gait cycle elite athletes have a more flexed hip angle. This reflects a reduction in hip extension at TO, which subsequently leads to a smaller angle at the point of maximum hip flexion. This may be indicative of the coordinative strategies required to achieve velocities >10.0m/s.

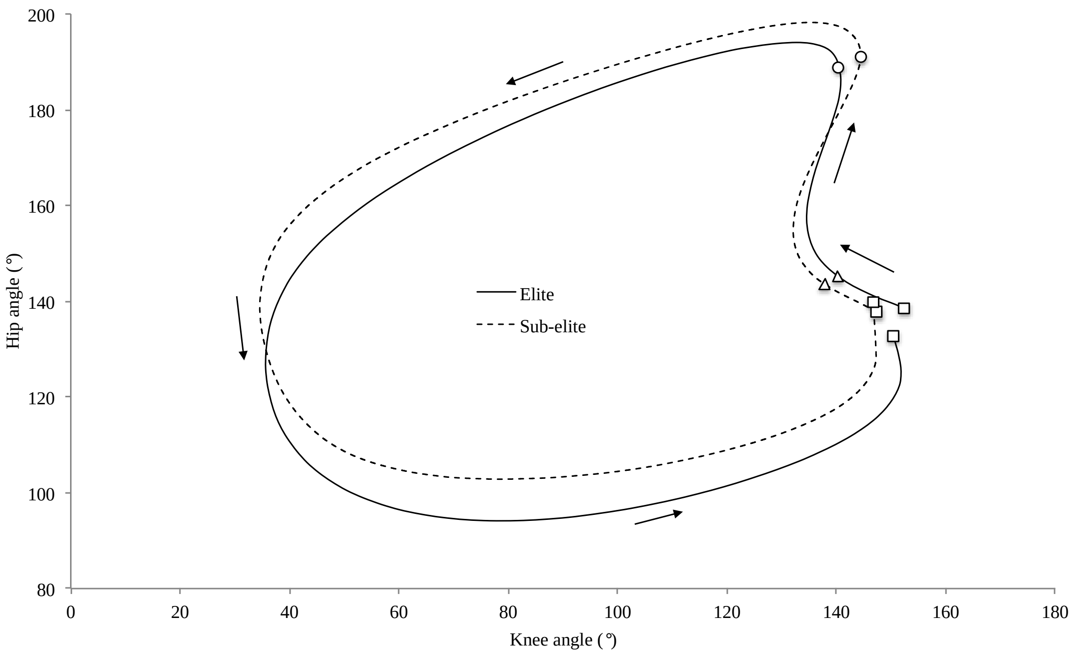


Figure 4-9 Profile of the HK coupling for an entire stride. Mean of n=10 elite athletes and n=10 sub-elite athletes. Square indicates point of TD, triangle indicates point of MS and circle indicates point of TO. Arrows indicate progression of gait cycle from TD→ MS→TO→TD.

The ensemble knee-angle coupling of an entire gait cycle for an elite and sub-elite sample is presented in Figure 4-10. Touchdown occurs on the right hand side of the plot and passes in an anti-clockwise direction. There is no difference in the ankle angle at TD between elite and sub-elite athletes, though as referred to earlier sub-elite athletes TD with a more flexed knee. In both groups the rate of flexion of the knee and ankle following TD is similar, with sub-elite athletes experiencing slightly more flexion at the ankle joint. The point of maximum knee and ankle flexion occurs at the same time. Following this elite athletes experience a greater degree of ankle extension in comparison to knee extension (steeper gradient) compared to the sub-elite athletes. Consequently the degree of maximum knee extension is greater in sub-elite athletes (as discussed earlier). In contrast the maximum ankle plantarflexion angle is greater in elite athletes than sub-elite athletes. Both sub-groups experience a phase of knee flexion with minimal change in the ankle angle (indicated as a flat line on the plot), however elite athletes are in a more plantarflexed position throughout this phase. Towards the point of maximum knee flexion elite athletes experience a gradual change in the angle, whereas sub-elite athletes see a sharp change in the knee angle proceeding the point of maximum knee flexion. This is accompanied by a smaller change in the ankle angle during this phase in comparison to elite athletes. In the latter stages of the swing the knee extends with minimal change in the ankle angle.

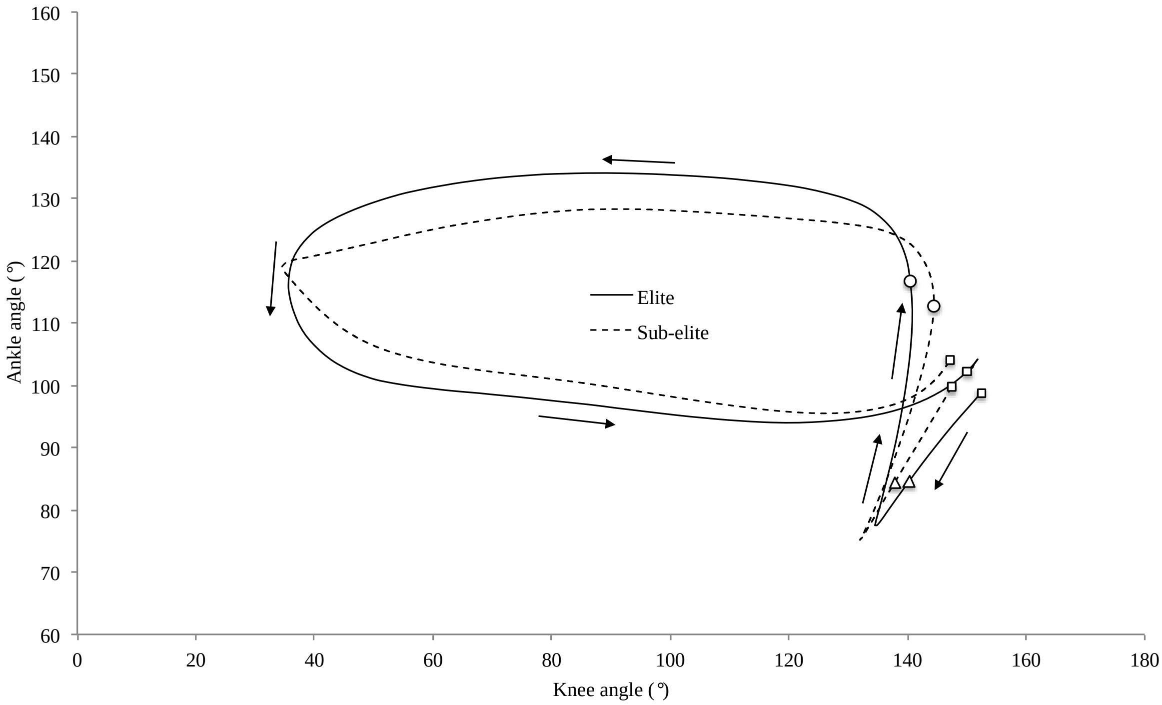


Figure 4-10 Profile of the KA coupling for an entire stride. Mean of n=10 elite athletes and n=10 sub-elite athletes. Square indicates point of TD, triangle indicates point of MS and circle indicates point of TO. Arrows indicate progression of gait cycle from TD→ MS→TO→TD.

Phase plots plot the angle of a joint relative to its angular velocity. Typically the angular and velocity data are normalised to +1 and -1 based on the maximum and minimum of the data set to facilitate comparisons across numerous joints and between subjects. The phase plots can be utilised to calculate the phase angle which is defined as the four-quadrant arctangent angle formed between the right horizontal and the line from the origin to the respective data point on the phase portrait. The CRP for the HK and KA joint couplings were determined by quantifying the difference between the phase angle of the distal and proximal joint at each time interval. The group ensemble CRP time history of the HK and KA couplings for the elite and sub-elite samples are presented in Figure 4-11. The group mean TD, MS, TO and TD times are marked on the graphs and were used to divide the gait into a stance and swing phase. The mean CRP and CRPv for the elite and sub-elite groups at TD, MS and TO are illustrated in Figure 4-12. The mean CRP and CRPv for the entire gait cycle and the stance and swing phases are illustrated in Figure 4-13.

The two couplings displayed similar amounts of relative phase at the onset of the step. The HK coupling displayed a relative phase of 75.2° indicating the proximal joint angle is greater than the distal, whilst the KA coupling had a relative phase of -77.2° indicating the distal angle is greater than the proximal. This is indicative of out-of-phase motion, which has previously been associated with transitions in the gait cycle (Hamill et al., 1999), in this case the transition from swing to stance. After TD the HK coupling tended towards more in-phase motion, in contrast the KA coupling tended to more out of phase motion resulting in a peak CRP of -153.2° at 10% of the gait cycle. At the point of MS the sub-elite group had a significantly more out-of-phase HK coupling than the elite sample. From MS up to the point of TO both couplings tend to a more in-phase motion. This coincided with a tend towards a more in-phase HK coupling of the sub-elite sample to reflect similar values to the elite sample. The HK coupling of the elite group was in-phase (0°) at exactly the point of TO, whereas the KA coupling didn't reach in-phase until just after the point of TO. The sub-elite group achieved in-phase motion 2% later in the gait cycle for both couplings compared to the elite group. When an average CRP is taken for the entire stance phase the KA coupling produced a larger group mean CRP (-98.6°) compared to the HK coupling (46.0°).

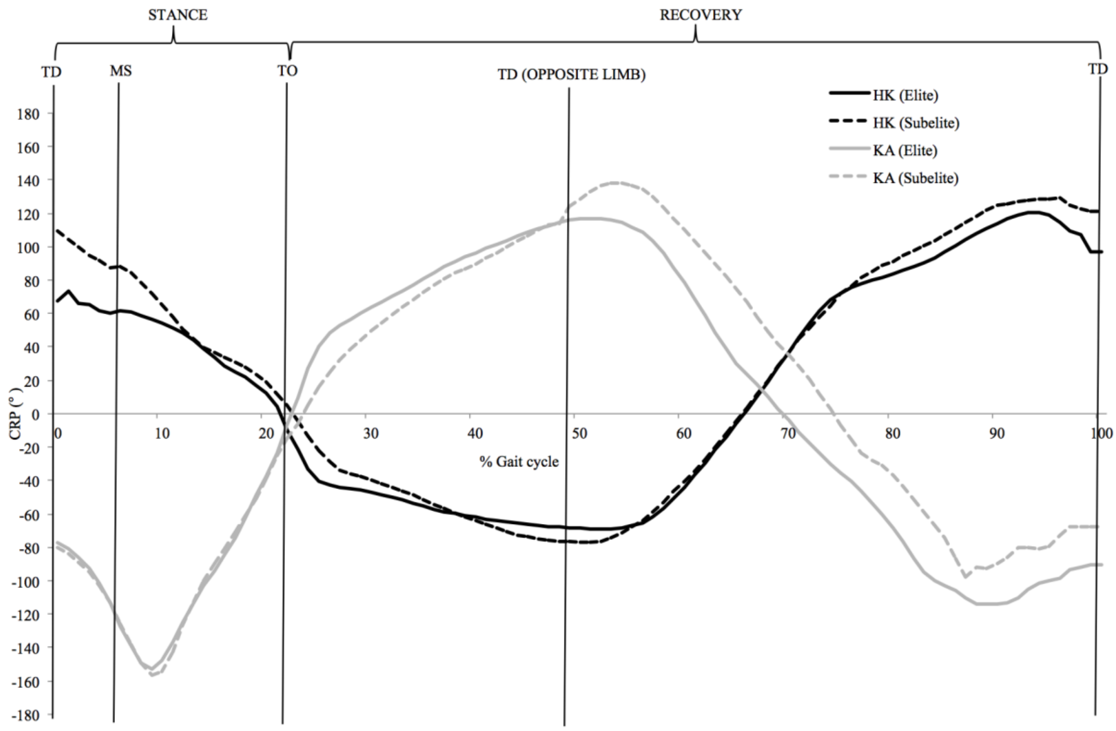


Figure 4-11 Ensemble CRP time history for a stride. Mean of n=10 elite athletes and n=10 sub-elite athletes

The early swing phase was occupied by a verge towards more out-of-phase motion (as in-phase had already been achieved at the point of TO). Interestingly in the early swing phase the sub-elite group exhibited more in-phase motion for both the HK and KA coupling compared to the elite group, however this was not significant. When expressed as a mean value for the early swing phase (defined as the phase from TO to TD of the contralateral limb) the mean CRP of the HK coupling was -52.3° and the KA coupling was 75.2°. As previously mentioned limiting the analysis to the point of TD of the contralateral limb fails to take into consideration the entirety of the path of the swing leg in the swing phase. Figure 4-11 indicates the HK coupling tends towards a more in-phase motion immediately after the initial TD of the opposite limb and achieves in-phase motion (0°) at 67% of the gait cycle. The phase patterns of the HK coupling were similar between both sub-groups for this phase of the gait cycle. The KA coupling also tends towards more in-phase motion, but doesn't reach in-phase until 71% of the gait cycle. The sub-elite group exhibited a greater out-of-phase motion for this coupling and a significantly greater maximum CRP value. Furthermore in-phase motion for the KA coupling was not reached until later in the gait cycle (75%). After this point both couplings tend towards more out-of-phase motion in the latter stages of swing. The HK coupling reaches a maximum CRP value of 120.74° very late in the swing phase (95% of the gait cycle), and tends back towards an in-phase motion of 97.2° by TD. In contrast the KA coupling reaches a maximum out-of-phase (for the swing phase) of -114.2° at 91% of the gait cycle, and then also tends towards more in-phase at TD. In the latter stages of the swing the sub-elite sample have a more in-phase KA coupling, but the HK coupling is more out-of-phase in comparison the elite group. Interestingly the phase angle for late swing is similar between the two sub-groups (as the lines are parallel on the plot), it just occurs at a later percentage of the total gait cycle for the sub-elite group. This indicates that whilst the two groups are adapting the same coordinative strategies it is the timings which differ. The mean CRP value for the entire swing phase (defined as the point of TO of one foot to TD of that same foot) was 6.8° for the HK coupling and 16.7° for the KA coupling. However these values are low due to the averaging of positive and negative values. If the absolute values are calculated the mean CRP of the HK coupling was 63.5° and 66.2° for the elite and sub-elite samples respectively. Similarly the CRP of the KA coupling was also similar for the sub-groups (77.0° and 75.1°) and there was no significant difference.

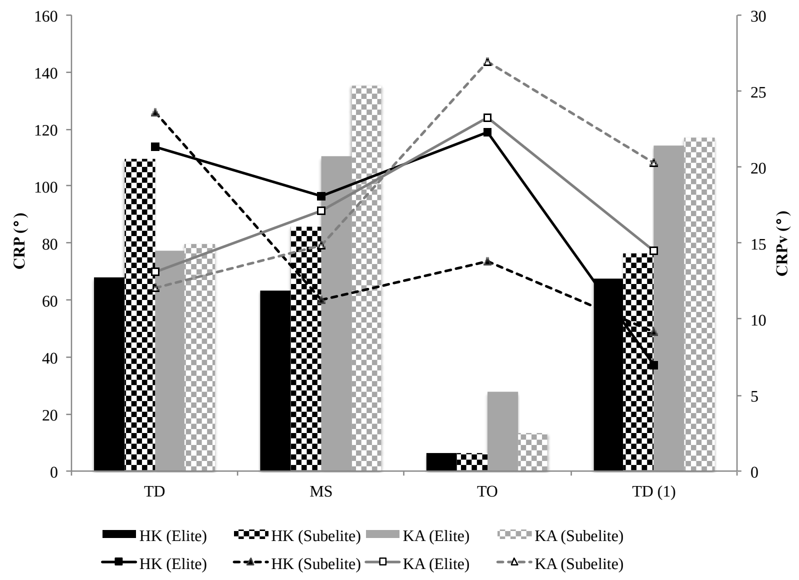


Figure 4-12 CRP and CRPv of the HK and KA coupling for both the elite and sub-elite groups at key time points in the gait cycle

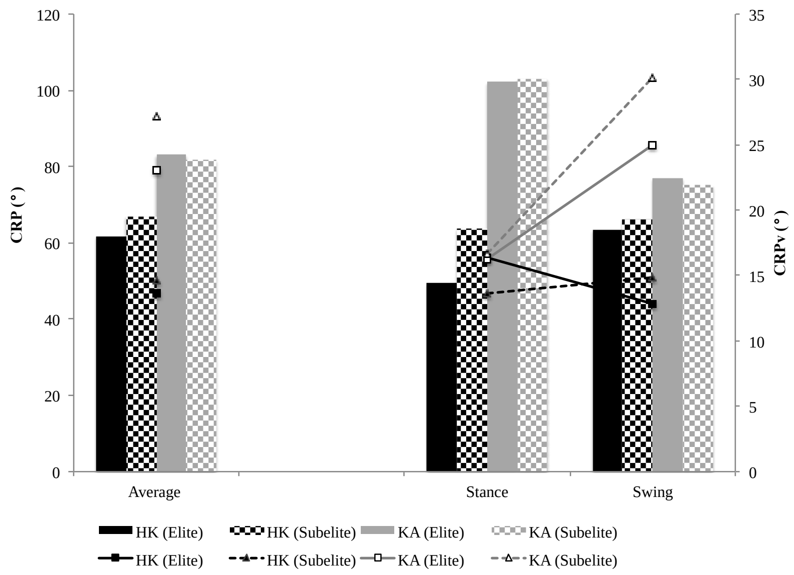


Figure 4-13 CRP and CRPv of the HK and KA coupling for both the elite and sub-elite groups averaged for a full gait cycle and stance and swing separately

A key component in the analysis of movement coordination is the role of variability within the system under investigation (Wilson et al., 2008). In order to investigate the effect of skill on the CRP variability the elite and sub-elite groups are plotted on the same graph (Figure 4-14).

The CRPv at TD was higher in the HK coupling (21.2°) in comparison to the KA coupling (13.1°). Immediately after TD the HK coupling reduced to a variability level similar to the KA coupling. Following MS the variability reduced in both the HK and KA coupling, and then increased again by the point of TO. The sub-elite group had greater variability in the HK coupling at TD in comparison to the elite group, however they had slightly less variability in the KA coupling, yet neither of these were significantly different. There are considerable differences in CRPv between the elite and sub-elite group in the latter stages of stance. Whilst the variability of the KA coupling is considerably higher in the sub-elite group this is accompanied by a much lower variability in the HK coupling. Subsequently it can be extrapolated that it is differences in the hip and ankle kinematics at this time point as opposed to the knee kinematics. The elite sample had higher variability of the HK coupling when averaged over stance which may be indicative of greater ROM, whilst the variability in the KA coupling was the same across both groups indicating a level of control over this coupling.

The variability decreased immediately post toe-off to approximately 10°. Whilst the elite group experience a peak CRPv at the point of TO the peak CRPv of the KA coupling in the sub-elite group occurs just prior to TO whilst the peak for the HK coupling occurs just after TO. In the early stages of swing the variability between the two sub-groups is similar. At the point of TD the HK coupling had a variability of 7° and the KA coupling 5° which again are comparable to the values reported in the current study. There was a significant difference in the variability of the KA coupling between the elite and sub-elite sample at this time point. From 33% of the gait cycle the sub-elite sample experience a sharp increase in the variability of the KA coupling to a peak value of 38.8° just prior to TD of the opposing limb. In contrast the elite sample only experience a gradual increase and value at TD of 13.3°. The high variability exhibited by the sub-elite sample is reflective of the variance in coordinative strategies of the swing leg at this time point. This suggests the elite sample are using a more reproducible HK and KA coupling motion and perhaps this is a mechanism associated with attaining high horizontal velocities. However it has been proposed that variability can be favourable as it facilitates the achievement of the same outcome from multiple strategies which can be critical in minimising injury.

The late swing phase (from TD of the opposing limb to final TD of the same limb) is illustrative of large variances in the CRPv which reflect the changes in the flexion and extension of the joints throughout this phase. Both couplings experience a peak in variability at approximately 65-70% of the gait cycle, followed by a trough at 80-85% and then a peak again from 90-100%. Throughout this phase the variability is higher in the KA coupling. From 50-80% the sub-elite sample had a higher variability of the HK coupling and a greater peak in KA variability. In contrast from 80-100% of the gait cycle the sub-elite sample had less variability than the elite group in the HK coupling. This same time phase was reflective of extremely high variability levels for the KA coupling. The elite sample experience one peak in variability of 65.2° at 94% of the gait cycle, whilst the sub-elite group experienced three successive peaks in variability of an average of 52.2°. However both sub-groups exhibited a decrease in the variability of this coupling at the point of subsequent TD.

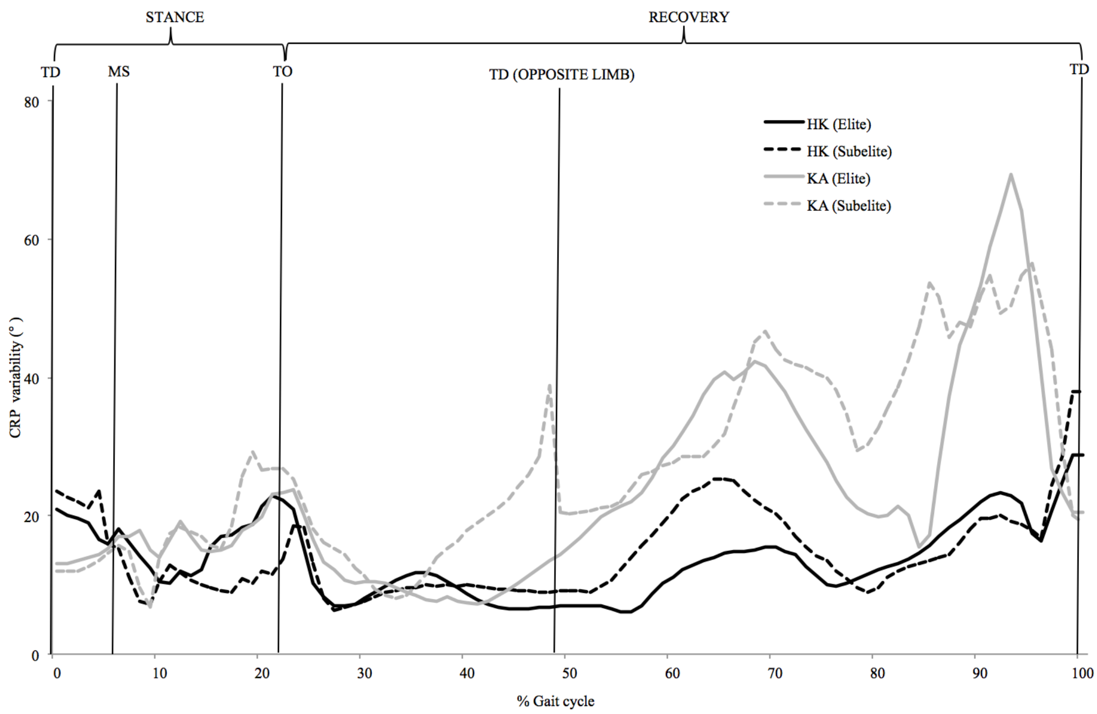


Figure 4-14 Ensemble CRPv time history for a stride. Mean of n=10 elite athletes and n=10 sub-elite athletes

4.4 Discussion

The comprehensive kinematics collected from a sample of elite sprinters within a competitive environment facilitates a unique approach for developing a technical model of elite maximal velocity sprinting. Previous research has aimed to identify the kinematics associated with elite sprinting (Mann et al., 1984), however these studies tend to be limited by sample size and subsequently their generalisation to the wider elite athlete population. Furthermore these studies use the empirical method for data collection and have selected variables based on existing literature and coaches' input. The arbitrary method in which variables are selected can lead to important variables being omitted or irrelevant variables bring included in the analysis (Nelson, 1985). The a-priori approach used in this thesis has used a deterministic model of sprinting to provide a systematic basis for determining which biomechanical parameters to measure. The aim was to quantify the parameters inherent to elite sprint performance. The inclusion of sub-elite and elite samples allows the identification of variables which are inherent to sprint performances >9.0m/s, and the variables which distinguish those performances to performances >10.0m/s. In order to facilitate the discussion the sprinting stride will be split into the touchdown, mid-stance, toe-off, early swing and late swing phases respectively.

4.4.1 Touchdown

The touchdown position in sprinting is crucial due to its influence on the magnitude of horizontal braking forces. There is a trade-off between a large D_{TD} which increases the step length and increases the ROM over which force can be applied, to a small D_{TD} which minimises the braking forces and the ground contact time, thus maximising step frequency. This can be reflected in a different equation of horizontal velocity proposed by Goodwin (2011) which is stance distance divided by ground contact time. It has been shown that better sprinters tend to favour a shorter contact time and shorter D_{TD} (Mann, 1985). This is achieved by properly preparing the leg for ground contact and by increasing the concentric strength of the hip extensors in order to develop the necessary propulsive force over the short ground contact time (impulse). This allows elite sprinters to minimise D_{TD} without sacrificing overall step length. The average D_{TD} was 0.26m and displayed a moderate correlation to horizontal velocity (r=0.490). Mann and Herman (1985) reported a D_{TD} of 0.25m, however it is not a true value as it is influenced by the leg length of the athlete. Subsequently a more reliable variable is the lower limb angles at TD. The joint angles at the hip and knee at TD of elite athletes were 147° and 151° respectively (Figure 4-7). Sub-elite athletes displayed slightly more flexion at touchdown which may be a coping mechanism in order to absorb the impact of touchdown. The stiffer limb adopted by elite athletes will enhance the loading of the stretch-shortening cycle in the early phase of stance. The foot speed at TD (relative to the COM) is imperative as increasing the speed of the foot relative to the COM will reduce the braking forces at TD. Whilst foot speed displayed a low correlation to maximal velocity this may be a result of it being a pre-requisite for sprinting at such velocities, and thus there is a little variance amongst the very elite which results in a weak correlation. Further research is required to establish the relationship between foot speed at touchdown and peak braking force. Sub-elite athletes displayed a greater hip extension velocity in the early phases of stance, which may be to overcome the greater degree of flexion at the point of TD. In contrast elite athletes displayed a greater average knee flexion velocity from TD through to MS (-122°/s), yet the range in angle was less (10°) than the sub-elite athletes (13°). The reduced ROM and greater velocity means the braking phase duration is shorter in elite athletes indicating it is favourable to performance. Based on the impulse-momentum relationship an increase in the braking force will necessitate an increase in propulsive force to maintain a constant horizontal velocity. The existing literature investigating sprint mechanics has only focused on the stance limb and has disregarded the position of the swing limb. The most important function of the swing leg is to get the leg back into position ready for the next ground contact, however during late swing the swing leg also serves to assist the stance leg at toe-off (Bosch & Klomp, 2005). Whilst the stance leg reflects a closed chain movement and the swing limb undergoes open chain movement the relationship between the two can give an indication of ability level. Both Bosch and Klomp (2005) and Mann (1985) recognised that at the point of TD the knees of the two limbs must at least be located side by side to prevent the loss of landing energy. In the current thesis there were substantial differences in the hip angle of the swing limb at TD between elite and sub-elite athletes, highlighting it as a key illustrator of elite athlete performance. Furthermore this variable displayed a strong correlation (r=0.689) to horizontal velocity. At the point of TD the hip angle of the swing limb was significantly smaller in elite athletes (197°) compared to sub-elite athletes (225°). This indicates the thigh is further forward relative to the vertical at this time point, and thus is further forward in the swing phase of the stride. This reinforces the notion of front side mechanics as proposed by Mann and Herman (1985). A variable favoured by sprint coaches is the thigh angle as this can be viewed on high-speed video without the need for digitisation and provides a quick indication of the effectiveness of the swing phase. The strong correlation between thigh angle and horizontal velocity (r=0.597) support the use of this variable for distinguishing between ability levels. The angle between the thighs was significantly smaller for elite athletes (14°) than sub-elite athletes (27°), which is indicative of a more effective swing phase. The out-of-phase motion of the HK and KA coupling at TD may be indicative of the need to adjust the lower limb coordination from an open chain swing to the closed chain nature of the stance phase (Gittoes & Wilson, 2010). The TD phase in maximal sprinting requires great demands on the lower extremity to attenuate a rapidly occurring impact and braking force (DeVita, 1994). The value for the KA coupling at TD is similar to the -90°

reported by Gittoes and Wilson (2010) and there was no significant difference between the elite and sub-elite sample. In contrast the sub-elite group had a significantly more out-of-phase HK coupling in comparison to the elite sample at the point of TD (109.47°), which is also nearer the 140° reported by Gittoes and Wilson (2010). The authors used a sample of 6 male athletes at a mean horizontal velocity of 8.567m/s, which is nearer to the mean horizontal velocity of the sub-elite sample (9.55m/s). Thus the HK coupling at TD may be a function of the skill level of the sample, and to achieve higher velocities athletes should aim for more in-phase (rotating in the same direction) of the hip and knee joints at the point of TD. Comparisons of the elite and sub-elite group provide insight into whether variability is desirable within a gait cycle. Trezise et al. (2011) found the better sprinter in their sample (n=2) had higher CRPv across the stride, but attributed this variability to maintain the hip ROM when under fatigue and thus is favourable. The sub-elite group had greater variability in the HK coupling but less variability in the KA coupling at TD in comparison to the elite group, yet neither of these were significantly different.

4.4.2 Mid-stance

Mid-stance is defined as the time point when the COM passes over the point of contact and is a critical time point as it represents the transition from the braking to propulsive phase of stance. Mid-stance occurred at a 25% of the overall stance phase. There were significant differences ($p<0.05$) between the elite and sub-elite athletes for the knee and ankle angles at the point of MS. Sub-elite athletes experienced 6° more flexion at the knee joint and 5° more flexion at the ankle joint. This was observed on the phase plot which was wider for sub-elite athletes indicating a greater ROM. The flexion at the knee and ankle joints indicates a lack of musculotendinous unit stiffness (MTU), which is one of the most important factors associated with high intensity performances such as sprinting (Fletcher, 2009). A greater degree of flexion is often indicative of an inability of athletes to produce sufficient vertical forces to withstand gravity at touchdown (Young, 2006). Whilst flexion is necessary to cushion the impact of ground contact too much compression of lower limbs would likely lead to a loss of energy, along with increasing the time spent on the ground which decreases step frequency. Therefore it is hypothesised that minimising the knee and ankle flexion at MS is inherent to elite performance, which coincides with the findings of

Ito, Fukuda, and Kijima (2008) who found a minimal change in knee angle throughout stance for Tyson Gay and Asafa Powell. The literature tends to report values at the point of maximum knee flexion, but this position lacks significance when related to movement principles. Maximum knee flexion occurred just after MS at the same time point as maximum ankle dorsiflexion. The peak hip (805°/s), knee (251°/s) and ankle (1182°/s) extension velocities all occurred in late stance approaching the point of TO. These values are larger than reported by Ito et al. (2008) for both Tyson Gay and Asafa Powell, but the authors concluded faster sprinters had a greater peak hip extension velocity and slower knee extension velocity, whilst maximum ankle extension velocity did not correlate to sprint velocity. The joint extension velocities during stance have been linked to the ground contact time and the development of propulsive impulse. The average hip velocity during stance was 575°/s which is higher than 429°/s reported by Mann and Herman (1985). The ability to exert force when angular velocities are high is one of the limiting factors to achieving top speed (Bosch & Klomp, 2005). Interestingly sub-elite athletes experienced a significantly higher peak knee extension velocity (450°/s), which had a strong correlation to velocity (r=0.537), suggesting a minimal velocity is favourable. It is hypothesised the high knee extension velocity experienced by sub-elite athletes may be necessity to overcome the greater range of flexion at MS rather than a performance benefit. This coincides with the findings of Ito et al. (2008) who reported peak knee extension velocities of only 50°/s and 68°/s for Gay and Powell respectively. Furthermore in their earlier research they reported the knee extension velocity for Carl Lewis was almost zero (Ito et al., 1994). There was a significant difference in the hip angle of the swing limb at MS with elite athletes indicating they are further forward in the swing phase at this time point (141°), which had a strong correlation to horizontal velocity (r=0.572). At MS the HK couplings display in-phase motion which indicates in the early phase of stance the hip and knee are rotating in the same direction, whilst the knee and ankle are rotating in opposite directions (out-of-phase). Gittoes and Wilson (2010) attribute the tend towards antiphase motion of the KA coupling in MS to allow a change in the coordination pattern from the braking to propulsion phase. In particular mid-stance is associated with a switch from ankle dorsiflexion to ankle plantarflexion. The fluctuation in this coupling at MS may be reflection of the movement pattern necessary to achieve the optimum braking to propulsion transition in maximal velocity sprint running.

4.4.3 Toe-off

The toe-off position in maximal velocity sprinting remains an area of contention. Sprint coaches and S&C coaches alike have supported the notion of triple extension which implies the hip, knee and hip all reach near full extension at the point of TO. However recent research and the findings of this study indicate this is not the case. Elite athletes actually reach their maximum knee extension (150°) prior to TO, and then flex again so the knee angle at TO is 142°. This is in contrast to Gittoes and Wilson (2010) who failed to observe this period of knee flexion, and Novacheck (1998) who reported ankle flexion prior to TO. The hip angle at TO was 162° and the maximum hip extension was actually reached after TO. Sub-elite athletes displayed more lower limb extension at TO, suggesting minimising extension is favourable to performance. Research has shown that overextending at TO can cause axial rotation which can only be compensated for by lengthening the next stride and therefore should be avoided (Bosch & Klomp, 2005). Force application in late stance is ineffective and therefore there are no advantages of lengthening the stance phase. Furthermore by minimising the extension this reduces the distance the COM has to travel which will reduce the swing time and thus maximise step frequency. This supports the theory of frontside mechanics pioneered by Mann (2010) that better sprinters minimise movements that occur behind the body (i.e. minimise extension at TO) and maximise the movements that occur in front of the body (i.e. maximise flexion in swing). A GRF trace of maximal sprinting indicates the majority of the vertical force is produced when the limb is in front of the COM, and there is minimal force generation once the point of contact is behind the COM (Mann, 1985). The productive knee and ankle muscle moments drop as soon as the athlete enters backside mechanics. The small increase in force is not worth the increase in ground contact time and therefore athletes should terminate ground contact in order to reach front side mechanics quickly. A high angular velocity of the thigh, generated by hip extensor musculature is commonly thought to be a performance-determining factor in sprint running (Hunter et al., 2004c). Ito et al. (1994) found maximum hip extension velocity was strongly correlated to sprint velocity for the gold and silver medallists at the 1991 World Championships. It was hypothesised at toe-off the lower limb couplings would display out-of-phase motion due to the transition from stance to swing. However both the HK and KA couplings were tending towards in-phase motion at TO. This was attributed to the lack of shock attenuation demands for this phase of the gait cycle in comparison to TD (Gittoes & Wilson, 2010). In-phase motion occurred 2% later in the gait cycle for the sub-elite group, which coincides with Gittoes and Wilson (2010) who investigated similar horizontal velocities to those achieved by the sub-elite group. Therefore it is proposed this may be attributed to the skill level (and thus horizontal velocity) of the athletes and athletes should aim for the hip and knee to extend in unison at the point of TO.

When an average CRP is taken for the entire stance phase the KA coupling produced a larger group mean CRP (-98.63°) compared to the HK coupling (46.02°). The larger CRP of the KA coupling would be expected due to the role of the ankle in the stretch-shortening cycle for the ensuing take-off phase. The HK coupling is likely to display more in-phase motion as the ground contact phase of sprinting is dictated by the extension of the hip and knee joints as the COM passes over the point of ground contact. The value for the KA coupling is larger than reported by Gittoes and Wilson (2010) (89.82°), however the HK coupling is less than reported by the authors (67.71°). There are considerable differences in CRPv between the elite and sub-elite group in the latter stages of stance. Whilst the variability of the KA coupling is considerably higher in the sub-elite group this is accompanied by a much lower variability in the HK coupling. Subsequently it can be extrapolated that it is differences in the hip and ankle kinematics at this time point as opposed to the knee kinematics. The stance phase is proposed to be the most important phase of the gait cycle in sprinting (Mann & Sprague, 1980). The stance phase is the only time when an athlete can exert forces to overcome gravity and air resistance. During stance the knee is responsible for weight acceptance (Bezodis et al., 2008), and the thigh segment plays a major role in producing the propulsive GRF to maintain maximal velocity (Hunter et al., 2004c). A decrease in variability would increase the control of the lower limb during this important phase. The elite sample had higher variability of the HK coupling when averaged over stance which may be indicative of greater ROM, whilst the variability in the KA coupling was the same across both groups indicating a level of control over this coupling.

4.4.4 Early swing

The swing phase is inherently important to sprint performance as the mechanically efficient swing of the limb sets up the other phases of the running stride for higher levels of mechanical efficiency. Better sprinters produce only enough vertical force to reposition the limbs and therefore a high angular velocity of the limbs is required (Mann, 1985). The early swing phase is defined as the hip flexion phase of the swing and occurred from 22-72% of the overall gait cycle. This is therefore a crucial phase as it forms 50% of the overall gait cycle, but has received little attention in the literature. Furthermore the importance of the position of the swing limb in relation to the stance leg as identified in this chapter stresses the importance of the swing phase. Although the swing limb cannot generate force when in the air it affects the loading through the stance limb (Bosch & Klomp, 2005). As aforementioned the hip reaches maximum extension early in swing (194°) which is comparable to the 190° reported by Gittoes and Wilson (2010). The hip then undergoes a phase of rapid flexion which was greater in elite athletes. The HK coupling plot indicates the hip and knee flex at the same rate in early swing, although the overall magnitude of the hip angle is smaller (more flexion) in elite athletes in comparison to sub-elite athletes (plot is lower). This is likely as the elite athletes minimised the hip extension at TO and therefore will be further forward in the swing phase in comparison to the sub-elite athletes. A maximum hip flexion velocity of -733°/s was observed towards the end of the hip flexion phase. The swing phase for the knee angle was the same between groups with both groups reaching maximum knee flexion (46°) at 55% of the gait cycle, which corresponds to the 40° reported by Gittoes and Wilson (2010). A small knee flexion angle is favourable as this reduces the moment of inertia of the swing limb, which increase the angular velocity of the limb and subsequently reduces the swing time. Ito et al. (1998) found the faster the sprint running velocity the greater the maximum knee angle (more flexion), and reported values of 41° and 28° for Gay and Powell respectively. Mann (2010) suggested maximum flexion at the knee should occur when the ankle of the swing limb crosses the stance leg, however this just provides an indication of the effectiveness of the swing phase and is not related to a biomechanical principle. Interestingly the KA plot (Figure 4-10) illustrates a sharp change in the knee angle in sub-elite athletes whereas elite athletes undergo a more gradual change. The sharp change in knee angle observed in sub-elite athletes may be a function of an inefficiency in the swing phase which means athletes have run out of time to gradually unfold the limb. Mann (2010) says athletes should delay the lower leg extension and control the flexion during swing, as observed in the joint coupling plot for the elite athletes. An additional key position that has been identified by previous authors is the point of maximum hip flexion (MHF). MHF angle was defined as the external angle between the trunk and thigh. This serves as a measure of the distance over which the hip angle has to extend prior to TD, and similarly the distance over which the lower limb has to accelerate approaching ground contact. This also increases the likelihood of a negative foot speed at the point of TD. Elite athletes reached a smaller hip flexion angle (103°) before the transfer into the extension phase. So whilst the hip ROM from TO to MHF was the same between elite and sub-elite athletes the elite athletes achieved this by minimising the amount of extension at TO and maximising the amount of flexion at MHF. In contrast to Gittoes and Wilson (2010) the early swing phase was occupied by a tend towards more out-of-phase motion. There was no difference between the HK and KA couplings for the elite and sub-elite samples, subsequently it is proposed that the horizontal velocity and/or skill level of the sample does not affect the intralimb couplings in the early swing phase.

4.4.5 Late swing

The late swing is characterised as the hip extension phase of the swing and comprises the final 28% of the overall gait cycle. The phase plot illustrates the hip extension velocity remained constant through this phase, and was higher in elite athletes than sub-elite athletes. Mann (2010) proposed that knee extension should be delayed until MHF has been reached. Maximum knee extension velocity (1195°/s) occurred just after MHF, and the knee then flexed again just prior to TD. Lower leg rotational speed at the point of TD is crucial as it affects the magnitude of braking forces. Therefore better sprinters complete knee extension during swing so there is lower leg flexion velocity at TD which reduces the braking force (Mann, 1985). This was observed at the 1991 World Championships as Ito et al. (1994) found the gold and silver medallists at the 1991 World Championships extended their knee at a lower angular velocity compared to a sample of sprinters analysed in the heats. Interestingly there was considerable variation in the ankle angle and angular velocity in the late stages of swing. Elite athletes displayed dorsiflexion in late swing whereas sub-elite athletes were plantarflexed. Dorsiflexion at TD is deemed favourable to develop pretension. Just prior to TD the ankle plantarflexes to allow a forefoot ground contact, and the maximum plantarflexion velocity was significantly higher in elite athletes (857°/s) in comparison to sub-elite athletes (697°/s). Neither the maximum or average hip or knee velocities during the swing phase demonstrated a strong correlation to maximum velocity, nor were there any significant difference between elite and sub-elite athletes. This agrees with the findings of Weyand et al. (2000) who found greater velocities are achieved with greater GRF rather than increased speed of the limbs.

4.5 Conclusion

A summary of the key parameters inherent to elite sprint performance, and the movement principles on which they are based is provided in Figure 4-15. This model can be used by sprint coaches to identify the deficiencies in an athlete's performance and the potential limiting factors to them achieving velocities exceeding 10.0m/s. Ground contact time was minimised by elite athletes by reducing the degree of knee and ankle flexion during ground contact and limiting full extension of the hip, knee and ankle joints at the point of TO. There were no differences in the position of the stance leg at TD between elite and sub-elite athletes, however there were differences in the swing leg stressing the importance of analysing the swing limb. Elite athletes had a smaller thigh angle at TD indicating the swing leg is further through the swing phase at this time point which is favourable to performance. Furthermore elite athletes achieved a greater maximum hip flexion position. This could be desirable as it maximises the distance over which the swing leg can be accelerated approaching ground contact. The coordination analyses indicate that whilst the overall coordination strategies between elite and sub-elite athletes are similar it is the magnitudes which differ. Sub-elite athletes have a greater hip angle throughout the stance and swing phase, and a smaller ROM of the ankle during the swing phase.

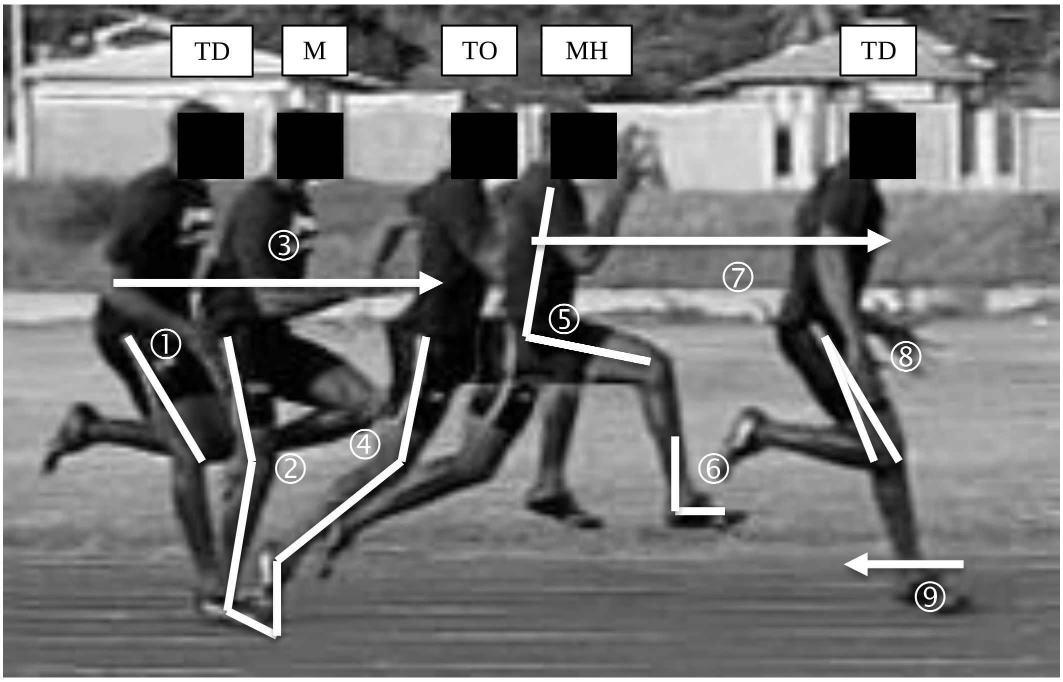


Figure 4-15 Kinematic technical model of maximal velocity sprinting (>10.0m/s)

	Technique	Movement principle	Recommended range
①	Maximise hip angle at TD	Reduces the distance between the contact point and the COM which reduces the braking impulse, reduces the amount of propulsive impulse necessary to maintain horizontal velocity	147 ± 6° (measured relative to vertical)
②	Minimise knee and ankle flexion at MS	Allows energy to be stored in the SSC cycle, reduces the time taken for the COM to travel therefore decreasing GCT which maximises SF	Knee: 141 ± 5° Ankle: 84 ± 4°
③	Maximise hip extension velocity but minimise knee extension velocity during stance	Active extension of hip increases speed COM passes over ground contact. Knee flexion should be minimised and therefore minimal knee extension velocity	Hip average: 571 ± 59 °/s Knee extension velocity: 250 ± 151 °/s
④	Minimise hip, knee and ankle extension at TO	Limit full triple extension as is not an effective force production phase, minimises backside mechanics, avoids axial rotation, reduces distance COM travels during stance which minimises GCT	Hip: 162 ± 6° Knee: 142 ± 6° Ankle: 116 ± 6°
⑤	Minimise hip angle of swing leg at MHF	Better athletes achieve high knee position which increases the distance over which the limb can accelerate towards the ground, can achieve higher velocities relative to COM, can reach ideal lower limb TD position	103 ± 6°
⑥	High flexion velocity of hip and knee in early swing	Aids effective swing phase, reach MHF position as soon as possible. High velocity of swing leg assists loading of stance leg	Hip max: -733 ± 97 °/s Knee max: -1086 ± 100 °/s
⑦	High extension velocity of hip and knee in late swing	Aids in achieving optimum lower limb position at TD, increase chance of negative foot speed at point of TD	Hip max: 567 ± 76 °/s Knee max: 1195 ± 133 °/s
⑧	Minimise thigh angle at TD	Knees should at least be side by side or swing leg knee in front of stance leg knee, indicates effective swing phase	14 ± 7° (angle between the two thighs)
⑨	Foot speed at TD	A negative foot speed at TD (relative to the COM) will reduce the peak braking force and therefore the necessary propulsive force to overcome it. Can reduce GCT	11.32 ± 1.23m/s

4.6 Chapter summary

This chapter aimed to characterise the mechanics of maximal velocity sprint running in elite athletes. Data were collected during competition to maximise external validity and in order to answer the research question ii – *which kinematic technique variables are associated with elite levels of maximal velocity sprinting?* The kinematics inherent to maximal velocity sprinting have been presented, and the comparison of 'elite' and 'sub-elite' samples identifies the kinematics critical to attaining sprint velocities exceeding 10.0m/s This adds to the body of literature regarding elite sprinting, however it fails to identify how these techniques were achieved. An understanding of the kinetics of maximal velocity sprinting alongside the joint kinematics would further understanding into how velocities >10.0m/s are achieved and would address research question iii - *which kinetic variables are associated with elite levels of maximal velocity sprinting?*

CHAPTER 5 – DEVELOPMENT OF KINETIC TECHNICAL MODEL OF MAXIMAL VELOCITY SPRINTING

5.1 Introduction

The kinematic analysis presented in the previous chapter provided insight into the techniques used by elite sprinters at maximal velocity. The observed kinematics are a result of complex muscular contractions and thus a kinetic analysis is therefore required to determine the underlying causes of motion (Winter, 1990). The GRF acting on sprinter is a major determinant of sprint performance (Morin et al., 2011). Early research only provided a descriptive analysis of the kinetics associated with maximal velocity sprinting (e.g. Mann (1981), Chapman and Caldwell (1983), Hamill, Bates, Knutzen, and Sawhill (1983)). More recent research has attempted to make an association between the changes in sprint kinetics and running velocity or vice versa (e.g. Brughelli, Cronin, and Chaouachi (2011), Weyand et al. (2000)). It has been well established that peak vertical and horizontal forces increase with increased running velocity (Nilsson & Thorstensson, 1989). However the majority of this research focuses on slow to moderate velocities (1.5-6.5m/s), with very little research targeted at the elite level (>10.0m/s). This is due to the difficulties associated with the collection of kinetic data which requires expensive and advanced equipment. Furthermore gaining access to elite athletes willing to undergo this type of analysis is increasingly difficult. Bezodis, Salo, and Kerwin (2007) have begun to address this gap in the literature and investigated the kinetics of maximal sprinting of two elite subjects sprinting at velocities >10.0m/s. However the variables reported were limited and the discussion was predominantly focused on the internal kinetics.

The deterministic model in Chapter 2 depicted how the kinematic variables are influenced by the GRF components (Figure 2-8). The flight distance is dependent on the resultant GRF at TO which is a combination of the horizontal and vertical components of force. The vertical component of GRF (Fz) in sprinting is related to an athlete's ability to halt the downward velocity of the COM at TD (due to gravitational force), and reverse it to produce an upward vertical velocity at TO (Miller, 1990). Athletes must develop sufficient vertical impulse in the short ground contact time available to project the athletes into the air long enough to reposition the limbs for the next step (Goodwin, 2011).

The current thesis aims to expand on this research by reporting the kinetics of running velocities >10.0m/s. Furthermore the current study will progress to discuss the relationships between sprint kinetics and the associated kinematics in order to discuss the movement principles hypothesised in the kinematic technical model of maximal sprinting in Chapter 4. In order to address research question iii - w*hich kinetic variables are associated with elite levels of maximal sprinting velocity?* – the aim of the study was to analyse the external kinetics produced by elite sprinters at the maximal phase of sprinting. The investigation between such kinetics and horizontal velocity will be discussed, along with the correlation to selected sprint kinematics. This will allow the previously identified kinematic aspects of technique to be discussed in more detail and to identify the kinetic aspects which contribute to performance.

5.2 Methods

Six international-level male sprinters provided written consent for data to be collected at their training sessions. The subjects were all members of the same sprint training group based at Lee Valley Athletics Centre and were coached by a UK Athletics accredited coach. Basic anthropometric measurements along with their 100m personal best times and 100m season best time for the 2012 track and field outdoor season are listed in Table 5-1. Data collection did not involve any invasive procedures (as was the case for all studies presented in the thesis) and was approved by the University of Salford Ethics Committee.

Table 5-1 Anthropometric data and 100m personal best of the subjects (* as of November 2011)

Athlete	Age (years)*	Height (m)*	Mass (kg)*	100m PB (s)*	2012 100m SB (s)
A	33	1.80	91.74	9.97	10.02
B	35	1.81	84.20	10.06	10.32
C	34	1.83	100.77	10.25	10.37
D	32	1.75	73.50	10.11	10.27
E	19	1.74	91.23	10.51	10.75
F	26	1.79	83.14	10.16	10.46

Data collections were carried out between November 2011 and June 2012 in the year leading up to the London 2012 Olympic Games. All athletes were injury free at the time of commencement of data collection. Data were collected at the Lee Valley Athletics Centre either on the indoor or outdoor track based on the discretion of the coach.

Previous studies have found movement may be modified by experimental set up (Wank, Frick, & Schmidtbleicher, 1998). These studies propose therefore that sporting performances must be studied in natural training conditions or in the competition environment. As kinetic data could not be collected during competition (due for the necessity of force plates on the tracks) all data were collected during existing training sessions. Data collection sessions were entirely non-invasive as to not interfere with sprinters technique, and were arranged to coincide exactly with the sprinters training schedule to ensure no change to the coach's planned programme, and thus external validity was maintained. In order to investigate the relationship between kinetics and sprint technique kinematic data was collected alongside the collection of kinetic data.

In order to obtain kinetic data of maximal velocity sprinting three Kistler force plates (Kistler Instruments 9287BA, Switzerland) were placed end-to-end to give a total force platform area of 1.80m x 0.40m. This was deemed sufficient to obtain a good ground contact on the force plate from the majority of trials without athletes having to adjust their natural running stride (targeting). The force platforms were placed in the centre of the running track, with the centre of the middle platform being 65m from the start to coincide with the position of the fixed camera and the centre of the Optojump. As the force plates are elevated from the ground (35mm) the force plates were surrounded by a wooden housing to prevent athletes from incurring an injury from slipping off the edge of the plate. The housing also included a gradual ramp up and down from the force plates so athletes could run over it without adjusting their running stride. The housing was then covered with Mondo synthetic track so athletes were able to wear running spikes to maintain validity. Data were sampled at 1200Hz. The first two force plates were connected to 1 trigger, with the 3rd force plate being connected to a separate trigger. Both triggers were manually activated by a researcher approximately 3 seconds before the athlete made contact with the plates. Where possible a trial where an athlete made clean contact with only one plate was used for future analysis. If a trial where an athlete spanned two plates was used for analysis the GRF from both plates were summed together (Exell, Gittoes, Irwin, & Kerwin, 2012).

A high-speed digital video camera (Casio EXILIM F) was mounted on a tripod, 10m from the centre of the running lane, with the centre of the lens 1.30m from the ground and 65m from the start line. The field of view was calibrated with a rigid frame measuring 1.20 x 1.06m. Images were collected using a shutter speed of 1/1000 and at a sampling frequency of 300Hz. Where light was insufficient the shutter speed was lowered and the exposure compensation was set to +2.0EV. A LDM device (Laveg LDM 300C, Jenoptik, Germany) operating at 100Hz was positioned 10m behind the start line in the centre of the lane to obtain data of the displacement of the lumbar region of the sprinter. A static trial prior to data collection was used to calibrate the LDM to allow the expression of all distances relative to the start line (0.00m). The LDM device was used to identify the maximum velocity reached in the trial along with the horizontal velocity at the point of contact with the force plate (65m).

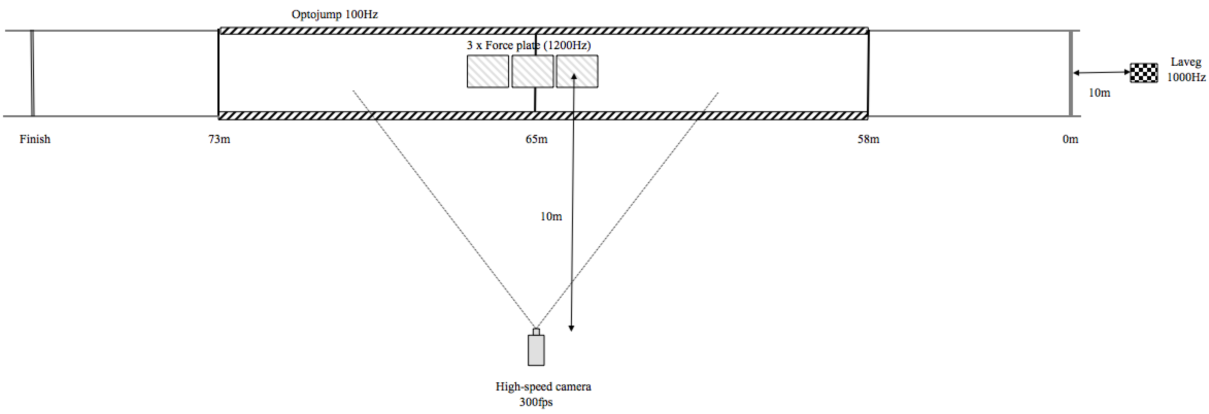


Figure 5-1 Equipment set-up for collection of kinetic data of maximal velocity sprinting

Kinetic variables were extracted from the raw GRF traces from a bespoke Excel spreadsheet. These variables were selected based on existing literature, the deterministic model in Chapter 2 (Figure 2-8) and the kinematic model presented in Chapter 4. A description of how the variables were calculated is provided in Table 5-3, and an illustration of these variables on a GRF trace is provided in Figure 5-2. Force values are reported in N and relative to each athlete's individual mass (BW). For five subjects a minimum of three trials were obtained where the athlete made a clean contact with the plate, and an average of the trials was taken. For athlete F only one successful contact with the plate was made across data collection sessions. Kinematic data were processed as detailed in Chapter 4.

The intraclass correlation (ICC) for the 16 kinetic variables was calculated using a total of three trials for each of the five subjects using SPSS. The results are presented in Table 5-2. All Fz variables exceeded the acceptable repeatability limit of 0.7 set by Baumgartner and Chung (2001), with peak Fz demonstrating the greatest reliability (0.908). Apart from peak braking force (0.743) the Fy variables displayed low repeatability. This can be attributed to the profile of the Fy trace as illustrated in Figure 5-3. On some occasions the Fy experienced two negative phases, whilst in other trials whilst the Fy experienced a double peak there was only phase that was negative. Thus the calculation of braking forces and impulses will be skewed based on the inclusion of either one of two negative phases. Furthermore within-individual differences in horizontal velocity between the trials will affect the repeatability of the key kinetic variables.

Table 5-2 Intraclass correlations (ICC) of GRF variables extracted for maximal velocity sprinting

Kinetic variable	ICC
Peak Fz	0.908
Time peak Fz from start	0.907
Peak E-RFD	0.836
Time from start	0.858
Vertical impulse	0.771
Average Fz	0.908
Peak braking force	0.743
Time from start	0.783
Duration of braking	0.191
Peak propulsive force	0.813
Duration of propulsive	0.327
Braking impulse	0.332
Propulsive impulse	0.807
Net horizontal impulse	0.403
Change horizontal velocity	0.967
Average Fy	0.103

The relationships between the components of GRF and horizontal velocity within the 23 successful trials were assessed using a Pearson's product moment correlation, classified as weak (0.10-0.29), moderate (0.30-0.49) and strong (>0.50) (Cohen, 1988). The associations between GRF variables and kinematics were explored with Pearson product moment correlations. The Pearson correlations were conducted on all trials where kinetic and kinematic data were collected simultaneously (23 in total). Due to the small sample size the non-parametic Wilcoxon signed-ranks test was used to assess kinematic differences between a high and low braking trial and a high and low vertical impulse trial. For each individual their trial with the highest peak braking force was compared to the trial where they produced the lowest peak braking force, and similarly a Wilcoxon signed-ranks test was performed between the trial where they produced the highest vertical impulse to the trial in which they produced the lowest vertical impulse. As only one trial was obtained for Athlete F the Wilcoxon test was only conducted on 5 athletes. Using the Wilcoxon Signed-Ranks Table a sample size of 5 is only sufficient for an alpha value of 0.10 and therefore statistical significance was set at $p<0.10$. Data were analysed using the statistical package SPSS (Version 20.0).

Table 5-3 Definition of kinetic variables used throughout the thesis

Variable	Definition
Contact time (s)	The time from when the vertical force threshold (20N) was exceeded until the vertical force dropped below the threshold again
Peak Fz (N & BW)	The maximum vertical force recorded for the trial
Peak E-RFD (kN/s & kN/s/kg	Equal to the change in force over one time point, smoothed over a 150ms period. The maximum value for the duration of the trial was selected.
Vertical impulse (Ns & Ns/kg)	The area under the Fz-time curve. Calculated by integrating force (Fz) over time (s).
Change vertical velocity (m/s)	Based on impulse-momentum relationship the change in velocity was calculated from the overall vertical impulse divided by time.
Average Fz (N & BW)	The average of Fz for the duration of the ground contact
Peak braking force (N & BW)	The peak negative Fy recorded for the trial
Braking phase duration (s)	The time from the onset of ground contact till the start of positive Fy force production. Where there are two phases of positive Fy duration the braking phase duration is calculated up to the 2^{nd} phase of positive force application
Peak propulsive force (N & BW)	The peak positive Fy recorded for the trial
Propulsive phase duration (s)	The time from the onset of the second phase of positive Fy till the end of ground contact
Ratio (brak:prop)	The ratio of time of the braking phase duration to propulsive phase duration
Braking impulse (Ns & Ns/kg)	The area of the negative Fy curve (or the sum of two curves if two negative phases). Calculated by integrating negative Fy over the braking phase duration.
Propulsive impulse (Ns & Ns/kg)	The area of the positive Fy curve (or the sum of two curves if two positive phases). Calculated by integrating positive Fy over the propulsive phase duration.
Net horizontal impulse (Ns & Ns/kg)	The propulsive impulse subtracted by the braking impulse.
Change horizontal velocity (m/s)	Based on impulse-momentum relationship the change in velocity was calculated from the net horizontal impulse divided by ground contact time.
Average Fy (N & BW)	Average horizontal force for the duration of the trial

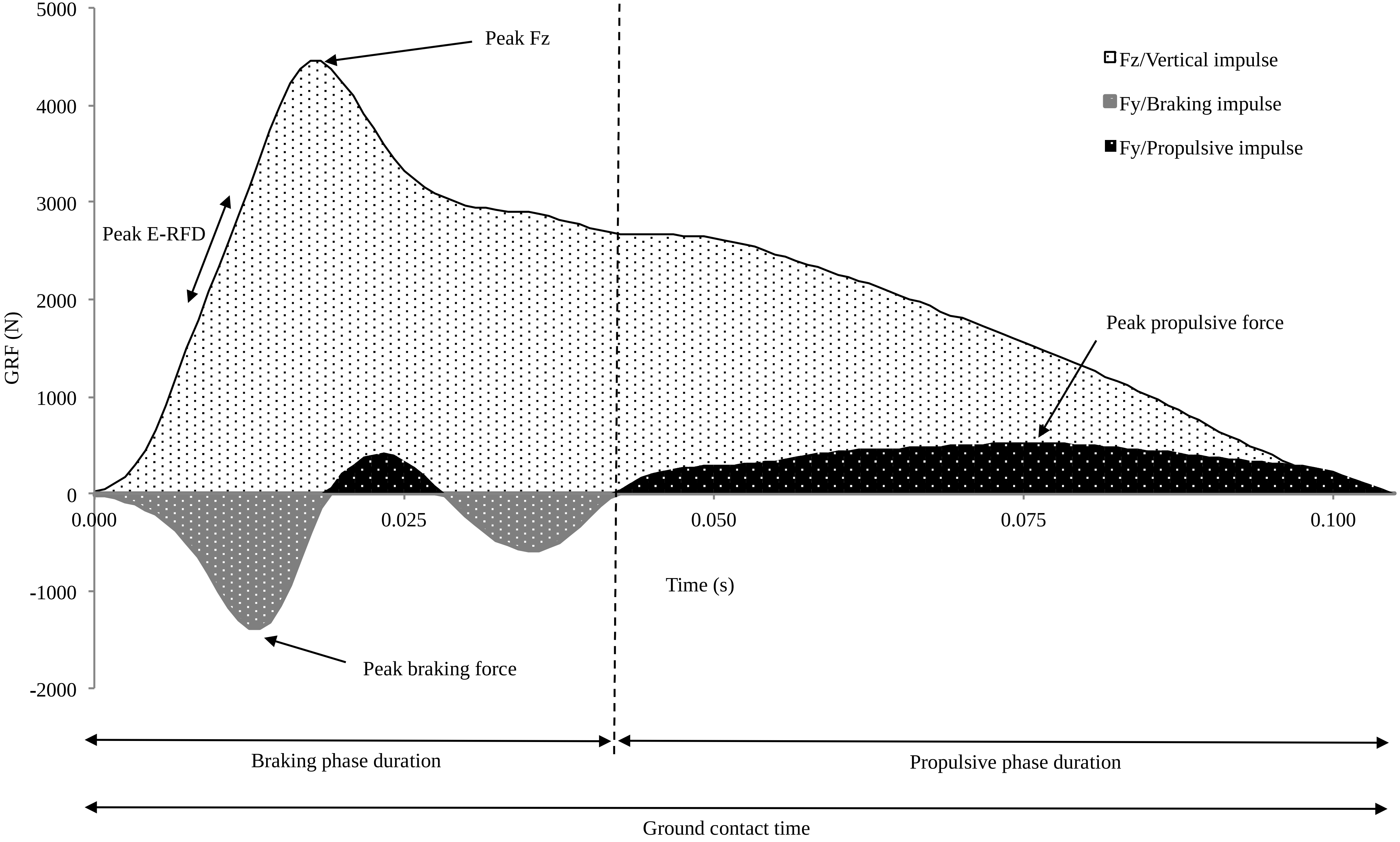


Figure 5-2 Illustration of kinetic variables used throughout the thesis

5.3 Results & Discussion

5.3.1 General kinetics

Over four separate data collections a total of 23 GRF traces were collected across a sample of six elite athletes. The fastest trial recorded was for athlete A who achieved a maximum velocity of 11.26m/s, which to the author's knowledge is the fastest trial for which external kinetics have been obtained in the academic literature. The GRF trace for this trial is illustrated in Figure 5-3. The vertical force (Fz) underwent a rapid increase to a maximum of 4449N within 0.02s, followed by a rapid decrease to 3000N, and then a more gradual decrease to the point of TO at 0.103s. This is in contrast to the GRF traces illustrated by Kyrolainen et al. (1999), Kuitunen et al. (2002) and Kawamori, Nosaka, and Newton (2013) who all show a 'bell-shape' for the Fz curve. There are further differences in the horizontal force (Fy). There is a peak negative force of -1384N, which is then followed by a phase of positive Fy, which then returns to a period of negative Fy before transferring to positive Fy leading up to TO. This pattern was evident within other athletes in the sample and was also observed by Bezodis et al. (2008) and Kawamori et al. (2013). The double negative phase is attributed to a shift in the position of centre of pressure during stance. It is unlikely the foot slipped on the surface as athletes wore running spikes and were on a Mondo track surface. More likely is the slippage of the foot within the spike which results in a minimal double negative phase. Whilst both Kuitunen et al. (2002) and Kyrolainen et al. (1999) identify this period of 'double peak' of the Fy trace they both report that the force remains negative throughout this phase. A further difference is the plateau of Fy in the latter stages of ground contact, whereas previous research reports this positive phase of Fy to represent a 'bell' shape.

A Pedotti diagram illustrates the resultant forces acting on the foot during sprinting using vectors, where the length of the line represents the magnitude of the force and the angle of the line represents the direction of the force application. The Pedotti diagram of the 11.26m/s trial is illustrated in Figure 5-4. The diagram clearly shows the braking forces at the point of TD that act in the opposite direction of movement. The resultant force then increases and tends towards a vertical direction until approximately 50ms of ground contact when a second period of negative force is experienced (as illustrated by the negative Fy on the previous graph). Following this the resultant force begins to decrease, but is orientated in a forward direction the same direction as sprinting. Korhonen et al. (2010) compared force variables in maximal speed running between young and older athletes. The mean horizontal velocity of the younger athletes was 9.50m/s which is close to the definition of an elite athlete as defined by this thesis. In addition the authors provided a Pedotti diagram to illustrate the resultant forces of a 10.0m/s trial. The authors do not provide the time on the x-axis, but the diagram shows a similar trace to the current study. The second braking phase is not evident, and the reduction in force towards the end of the stance phase is much more gradual.

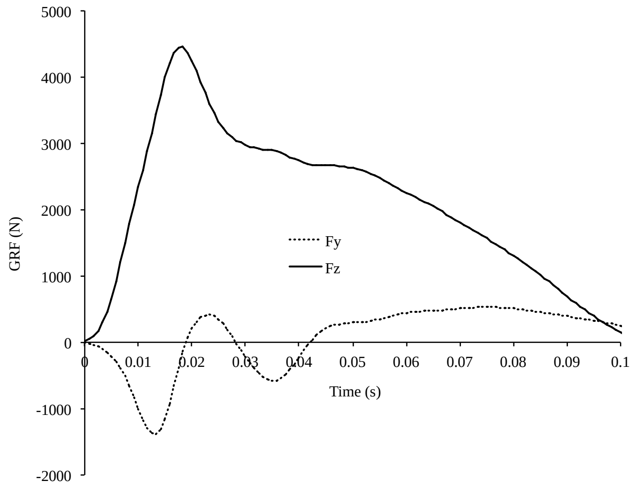


Figure 5-3 GRF trace of maximal velocity sprinting for athlete A (11.26m/s)

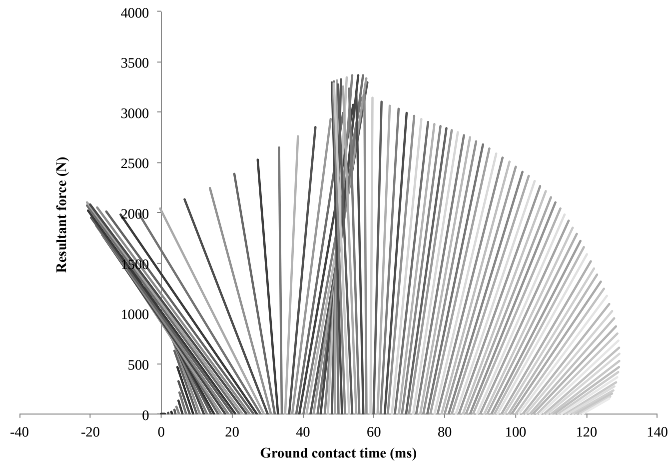


Figure 5-4 Pedotti diagram of maximal velocity sprinting for athlete A (11.26m/s)

The average values of the key kinetic variables for each subject are presented in Table 5-4. The mean ground contact time across all trials was 0.100s (calculated from the GRF trace). This GCT is less than reported in the majority of the literature investigating the kinetics of sprinting. It is well known that GCT decreases linearly with speed (Luhtanen & Komi, 1978), and therefore shorter GCT would be expected in the current study due to the higher velocities.

The mean peak Fz was 3176N (3.69BW). The greatest Fz recorded (4449N/4.89BW) was observed in the fastest (11.26m/s) trial (Figure 5-3), which agrees with the notion proposed by Weyand et al. (2000) that greater running speeds are associated with greater GRF. This value is comparable to those reported by Bezodis, Salo, and Kerwin (2009) for a male sprinter at a velocity of 10.37m/s (3240N), but is considerably larger than reported by Morin et al. (2012) (2.07BW) and Weyand et al. (2000) (2.14BW) which can be attributed to the slower velocities reached in their research.

The E-RFD has important functional consequences as it determines the force that can be generated in the early phase of muscle contraction (0-200ms) (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002). It is therefore of particular relevance in maximal velocity sprinting when the ground contact time is only 100ms. The mean peak E-RFD was 183.6kN/s. Until now the peak RFD has not been reported for the maximal velocity phase, however Coh, Jost, Skof, Tomazin, and Dolenec (1998a) found a correlation between the RFD in the sprint start and the associated kinematics. Slawinski et al. (2010) also reported RFD for the sprint start and found elite sprinters had a greater RFD (15.6kN/s) than well-trained sprinters (8.5kN/s), and subsequently warrants its investigation as a performance descriptor at maximal velocity.

Based on the impulse-momentum relationship the change in velocity is dependent on the magnitude of the impulse. Impulse takes into account the time over which force is applied, and has been the variable of interest in the research by Hunter et al. (2005) and Coh et al. (1998a). The mean vertical impulse in the current study was 90.89Ns, which resulted in a 1.03m/s increase in vertical velocity. The role of vertical impulse in maximal sprinting has received little attention in the literature. It has been proposed the vertical motion should be minimised to avoid increasing the flight time, and subsequently decreasing the SF. However vertical motion is necessary to provide the time for the reposition of the limbs in the swing phase and to increase the likelihood of a negative foot speed on the subsequent ground contact. The link between the vertical impulse and horizontal velocity will be discussed later in this chapter.

The role of horizontal force (Fy) in maximal velocity sprinting is to maintain a constant horizontal velocity. As velocity is being maintained the net horizontal impulse should be zero. The net horizontal impulse was 9.13Ns, a positive value indicating the propulsive forces slightly outweigh the braking phases. This resulted in a net increase in horizontal velocity of 0.10m/s over the duration of the ground contact, however this is perceived as minimal. The mean Fy in the current study was 89.89N (0.10BW). A typical horizontal GRF trace of maximal velocity sprinting indicates phases of both negative Fy and positive Fy (Figure 5-3). These are termed the 'braking' and 'propulsive' phases respectively. The peak braking force in the current study was -826.86N (-0.97BW). Surprisingly no existing literature has reported this value at maximal velocity which is surprising due to the proposed effect of braking force on horizontal velocity. Whilst they did not report the peak braking force Mero and Komi (1986) found that the average resultant braking force was -2257N, although this was during supramaximal sprinting. A peak braking force of -1.558N/kg has been reported for the acceleration phase of sprinting (Sleivert & Taingahue, 2004), however due to the difference in kinematics of this phase comparisons are limited. More commonly the braking phase is reported as a braking impulse which takes into account both the force and duration of the braking phase. Coh et al. (1998) report a braking impulse of -10.93Ns which is similar to the -10.37Ns reported by the current study. The relationship between kinematic variables and the magnitude of braking forces will be discussed later in this chapter. The peak Fy of the propulsive phase was 546.34N (0.64BW), which is smaller than the peak braking force. However as the braking force is an impact force it is likely to be much higher. The mean time of the propulsive phase was 0.064s which is longer than the braking phase (0.037s), and subsequently the propulsive impulse (19.47Ns) was greater than the braking impulse (-10.37Ns). The duration of the propulsive phase is similar to that reported in the literature (Table 2-4). As aforementioned the overall GCT in the current study was less than that reported by the literature, and hence it can be concluded this is due to a shorter braking phase duration as opposed to a shorter propulsive phase. When represented as a percentage of the overall ground contact the braking phase of the current study only forms 37% of the overall GCT, which is similar to that reported by Coh et al. (1998) (38%) but shorter than reported by Bezodis et al. (2007) (43%), Kyrolainen et al. (1999) (47%) and Belli, Kyrolainen, and Komi (2002) (48%).

Table 5-4 Mean (±SD) kinetic variables of maximal velocity sprinting for six subjects

Subject	Horizontal velocity at 65m	Weight	Contact time	Peak Fz		Peak E-RFD	Vertical impulse		Change vertical velocity	Average Fz		Peak braking force		Braking phase duration
	m/s	N	s	N	BW	kN/s	Ns	Ns/kg	m/s	N	BW	N	BW	s
A	10.28	899.73	0.106	3529	3.92	181.1	102.48	1.12	1.12	1858.62	2.07	-983.16	-1.09	0.044
B	10.01	826.15	0.090	3271	3.96	211.3	96.00	1.14	1.14	1884.70	2.28	-930.25	-1.13	0.034
C	10.00	988.60	0.108	3704	3.75	251.1	109.19	1.08	1.08	1990.63	2.01	-867.43	-0.88	0.037
D	9.88	721.25	0.092	2483	3.44	130.7	58.86	0.80	0.78	1374.88	1.85	-651.76	-0.90	0.031
E	9.92	894.83	0.102	3138	3.51	192.2	100.24	1.10	1.10	1869.46	2.09	-693.38	-0.78	0.034
F	9.46	815.60	0.103	2929	3.59	142.4	78.57	0.95	0.95	1575.91	1.93	-835.15	-1.02	0.039
Mean	9.93	857.69	0.100	3176	3.69	183.6	90.89	1.03	1.03	1759.03	2.04	-826.86	-0.97	0.037
±SD	0.27	91.29	0.008	437	0.22	40.2	18.76	0.13	0.14	233.52	0.15	130.62	0.14	0.004

Subject	Peak propulsive force		Prop. phase duration	Ratio	Braking impulse		Propulsive impulse		Net horizontal impulse		Change horizontal velocity	Average Fy	
	N	BW	s	%	Ns	Ns/kg	Ns	Ns/kg	Ns	Ns/kg	m/s	N	BW
A	576.93	0.64	0.063	41	-12.62	-0.14	21.24	0.23	8.57	0.09	0.09	81.12	0.09
B	606.50	0.73	0.056	36	-10.17	-0.12	19.93	0.24	9.70	0.12	0.11	107.23	0.13
C	514.98	0.52	0.072	36	-10.07	-0.10	20.85	0.21	10.70	0.11	0.11	97.21	0.10
D	439.69	0.61	0.061	36	-8.49	-0.12	15.22	0.21	6.67	0.09	0.09	72.07	0.10
E	563.22	0.63	0.068	33	-9.64	-0.11	20.36	0.22	10.68	0.12	0.12	105.06	0.12
F	576.73	0.71	0.064	38	-11.25	-0.14	19.19	0.23	7.86	0.09	0.10	76.68	0.09
Mean	546.34	0.64	0.064	37	-10.37	-0.12	19.47	0.22	9.03	0.10	0.10	89.89	0.10
±SD	60.20	0.08	0.006	3	1.42	0.02	2.20	0.01	1.62	0.01	0.01	15.19	0.02

5.3.2 Relationships between horizontal velocity and external kinetics

The current thesis is the first research to report such comprehensive external kinetics for sprint velocities >9.0m/s. Due to the lack of literature regarding the kinetics at such high velocities there is little knowledge regarding how the kinetics of sprinting can improve performance. Once such method that has been adopted by authors is the correlation of key kinetic variables to sprint velocity.

There was a moderate positive correlation (r=0.484) between horizontal velocity and average Fy (relative to BW), indicating Fy increased as velocity increases which is comparable to that reported by the literature. Nummela et al. (2007) reported that average Fy increased linearly with velocity from 5m/s to maximal, and average Fy (relative to BW) was significantly correlated to maximal velocity (0.56). However this was with a sample of endurance runners and therefore 'maximal' ranged from 7.20m/s to 9.40m/s which are velocities slower than the current study. Kuitunen et al. (2002) also reported an increase in Fy as running velocity increased from 70-100% in a sample of male sprinters, with 100% representing 9.73m/s. Yet it is important to note that the focus of the aforementioned research articles is how force production changes as an athlete increases their speed and thus represents a much larger range of velocities, whereas the current study looks at a range of maximal velocities. Subsequently the appearance of increasing horizontal force when running at higher velocities is actually an indicator of coping with the reduction in ground contact time.

At maximal velocity the horizontal velocity should be constant, and thus the net horizontal impulse should be zero. The horizontal impulse is a combination of a negative (braking) phase followed by a positive (propulsive) phase. Therefore in order to maintain a net horizontal impulse of zero the propulsive impulse must be sufficient to overcome the braking impulse. The limiting factor to attaining a greater maximum velocity is the point where contact time is so short that all effort must be directed vertically in order to overcome gravity, and therefore cannot produce any horizontal impulse in order to increase velocity (Goodwin, 2011). The aim must be to decrease the braking impulse, and subsequently the propulsive impulse necessary to overcome it so that contact time can be minimised. There was a moderate positive correlation between sprint velocity and net horizontal impulse (r=0.488), yet when divided into the respective components the magnitude of the braking impulse had a strong positive correlation to velocity (r=0.620) whereas the propulsive impulse had a weak positive correlation to velocity (r=0.012). This disagrees with the findings of Kyrolainen et al. (1999) who reported that the average Fy in the propulsive phase was more influential on overall velocity than Fy in the braking phase. Similarly Nummela et al. (2007) found that the average Fy of the propulsive phase was significantly correlated to horizontal velocity, whilst the average Fy of the braking phase was not. However these authors only investigated the average Fy with no consideration to the temporal components of the force application and the time over which it was applied. Current theories believe the braking impulse is a negative entity, yet the positive correlation between braking impulse and velocity actually indicates higher velocities are accompanied by higher braking impulses. This is opposite to what might be expected as the braking impulse will cause a decrease in horizontal velocity and thus is disadvantageous. However Mero and Komi (1986) found the average resultant braking force increased from 1314N when running at 4.95m/s to 2257N under supramaximal conditions. Kuitunen et al. (2002) also reported an increase in the peak braking force with an increase in speed. Cavagna, Komarek, and Mazzolen (1971) proposed that the braking force could be involved in the storage of elastic energy and therefore may have advantageous properties. Further Putnam and Kozey (1989) highlighted that it is unknown if the braking GRF is related to other mechanical properties which affect performance, such as the propulsive and vertical GRF components and/or SL and SF.

Due to the constant horizontal velocity at the maximal phase of sprinting research tends to look at the relationship between the vertical components of GRF and velocity. Current literature has only investigated velocities up to 7.0m/s and very little is known about velocities greater than this. There was a very weak correlation between average Fz and horizontal velocity (r=0.151). This coincides with Brughelli et al. (2011) who found a weak correlation of 0.13 between average vertical force (relative to body mass) and horizontal velocity. The authors fail to report the actual velocities (only reported as a percentage of maximum) and therefore it is difficult to extrapolate these results further. Nummela, Keranen, and Mikkelsson (2007) reported Fz remained constant at velocities >7.0m/s, which also coincides with the findings of Kuitunen et al. (2002) and Kyrolainen et al. (1999). In contrast Weyand et al. (2000)

used a regression analysis to conclude that the average vertical force was 1.26 times greater for an individual sprinting at 11.1m/s in comparison to an individual at 6.2m/s. However the test was conducted on a treadmill which has been shown to affect the kinetics of the ground contact phase in comparison to over ground running (Wank et al., 1998). Most importantly the range of velocities is much larger than in the current study, and thus regressions are likely to be stronger. Whilst they show how to increase from slower velocities, the research does not discuss changes in kinetics at the higher end of the velocity spectrum (>9.0m/s). There was a comparable weak correlation between peak vertical Fz (relative to bodyweight) and maximal horizontal velocity (r=0.120). Both Mero and Komi (1986) and Nilsson and Thorstensson (1989) found no increase in peak Fz with increased velocity. Kuitunen et al. (2002) reported peak Fz was consistent as sprinters increased their speed from 70% (7.00m/s) to 100% (9.73m/s) velocity. These maximal speeds are comparable to the current thesis and thus a similar relationship may be expected. The weak correlations between the both average and peak Fz and horizontal velocity can be attributed to the lack of temporal consideration. The change in vertical velocity is proportional to the vertical impulse, and thus the time over which the vertical force is applied must be taken into consideration. A slower velocity might be associated with a greater average Fz, but if this is achieved as a result of a longer ground contact time this is disadvantageous to sprint performance as step is negatively affected.

There was a weak positive relationship between maximal horizontal velocity and relative vertical impulse (r=0.138). Whilst the greatest horizontal velocity (11.26m/s) corresponded with the greatest vertical impulse (1.25Ns/kg), the slowest horizontal velocity recorded (9.43m/s) had a similar vertical impulse of 1.24Ns/kg. The weak relationship between vertical impulse and velocity is in contrast to the conclusions made by Weyand et al. (2000) that faster running speeds are achieved by the amount of force applied to the ground as opposed to how rapidly the limbs are repositioned in the air, however the negation of vertical impulse limits these conclusions. The role of vertical impulse at maximal velocity is unclear and the weak correlation to horizontal velocity can be attributed to the need for an optimum level based on the individual relationships between SL and SF. Vertical impulse is necessary to provide the vertical lift necessary to reposition the limbs in the swing phase and to increase the likelihood of a negative foot speed at the next ground contact. However too much vertical motion would increase the flight time, and subsequently decrease the SF. The findings in Chapter 3 indicated a strong relationship between SF and horizontal velocity, with the aim of maximising SF. Furthermore Salo et al. (2011) found SF to be individually reliant due to its interrelationship with SL. Therefore it is proposed that the weak relationship between vertical impulse and velocity is due to individual differences in SF. There was a strong correlation (r=0.573) between vertical impulse and SF thus proving this theory. Athletes with a high vertical impulse had a lower SF, but this coincided with a higher SL. Subsequently the individual variation in the SL/SF relationship leads to a weak correlation between vertical impulse and horizontal velocity.

5.3.3 Relationships between external kinetic and kinematics

The conclusions of Chapter 4 identified the inherent kinematics of maximal velocity sprinting that are necessary for elite performance based on key biomechanical principles. The findings from this chapter can be used to establish whether the kinematics mentioned do relate to the kinetic variables proposed. The deterministic model developed in Chapter 2 (Figure 2-8) can be used to understand how the kinetic components of force relate to the spatiotemporal variables of maximal velocity sprinting. Analysis of technique must be based on how changes in technique will enhance ground reaction force production. Typically research combines kinetic and kinematic data through inverse dynamics analysis to calculate the internal joint moments associated. However this necessitates 3-D motion capture systems to accurately define the joint coordinates and therefore is impractical for use within in-field testing. Inverse dynamics only gives a net joint moment and is therefore still an incomplete analysis. Subsequently different methods have studied the relationships between kinetics and kinematics as an alternative. Lockie, Murphy, Schultz, Jeffriess, and Callaghan (2013) performed multiple correlations between kinetic variables and the SL and GCT at 0-5, 5-10 and 0-10m of a sprint. Hunter et al. (2005) adopted a different approach and aimed to identify the difference in sprint technique between a 'high' and 'low' braking trial and a 'high' and 'low' propulsive trial by conducting paired t-tests between the kinematics of the two. However this was for the acceleration phase of the sprint and the findings cannot be extrapolated to the maximal velocity phase. Coh, Jost, and Stuhec (1998) aimed to identify which kinematic and kinetic variables characterise the skill of sprinting across different ability levels using 7 female elite sprinters. The authors measured 12 kinetic variables, and then used a Pearson correlation coefficient to identify which kinetic parameters significantly correlated with sprint velocity.

The findings of Chapter 4 identified that elite athletes have a greater hip angle and foot speed at TD than sub-elite athletes. It was proposed this may related to the manipulation of the braking forces, as higher peak braking forces were observed in the higher velocity trials. As the peak braking force occurs immediately post TD (0.015s) it can be confidently concluded that it is determined by the kinematics of the lower limb at TD. By correlating the peak braking force from the 23 trials to the corresponding kinematics from these trials the relationships can be investigated (Table 5-5).

Table 5-5 Pearson correlations (r) between peak braking force (BW) and TD kinematics

	Mean (±SD)	r
Hip angle at TD (°)	147.22 (5.41)	0.355
Knee angle at TD (°)	147.80 (7.43)	0.305
Hip extension velocity at TD (°/s)	434 (160)	0.284
Knee flexion velocity at TD (°/s)	-273 (302)	0.371
Ankle flexion velocity at TD (°/s)	-465 (134)	0.439
Velocity of the swing leg at TD (°/s)	-430 (344)	-0.381
Foot speed at TD relative to COM (m/s)	9.91 (1.41)	0.312

The hip and knee angles all exhibited a moderate positive correlation to peak braking force. As peak braking force is a negative value a positive Pearson correlation indicates a smaller peak braking force is associated with a larger angle (i.e. more extension). The joint angular velocities at TD are deemed to be important to the braking force as they dictate the speed the limb is travelling relative to the COM, and subsequently the degree of the braking force experienced at TD. The hip extension velocities and knee and ankle flexion velocities at the point of TD all showed a moderate positive correlation to the peak braking force, indicating higher velocities are associated with a lower peak braking force. This illustrates that if a peak braking force does have some advantageous properties, for example the storage of elastic energy (Cavagna et al., 1971), it may be beneficial to reduce the leg angle and leg speed at touchdown. However purely using a Pearson correlation masks the individual differences that athletes may adopt between a high braking and low braking trial. Therefore a within-subject comparison as adopted by Hunter et al. (2005) was used to identify the kinematic differences between a high-braking and low-braking trial using a Wilcoxon signed-ranks test. Based on the findings of Chapter 4 the variables assessed for a high braking and low braking trial were hip and knee angle at TD, foot speed at TD, hip and knee angular velocities at TD and the velocity of the swing leg. The kinematic parameters for the high and low braking trials were plotted on individual radar plots. Radar plots have the added advantage of not only illustrating the differences in key parameters between the high and low braking trials, but also indicating the individual differences in these parameters across the 5 members of the sample. A uniform pentagon shape would indicate a similar angle/velocity across the sample, whereas a skewed pentagon indicates individual differences. The radar plots for the key kinematic variables are provided in Figure 5-5, the p values are indicated on each plot individually. In addition the GRF trace of a high and low-braking trial for a representative athlete (Athlete A) were plotted against the joint angle profiles for the respective trials (Figure 5-7).

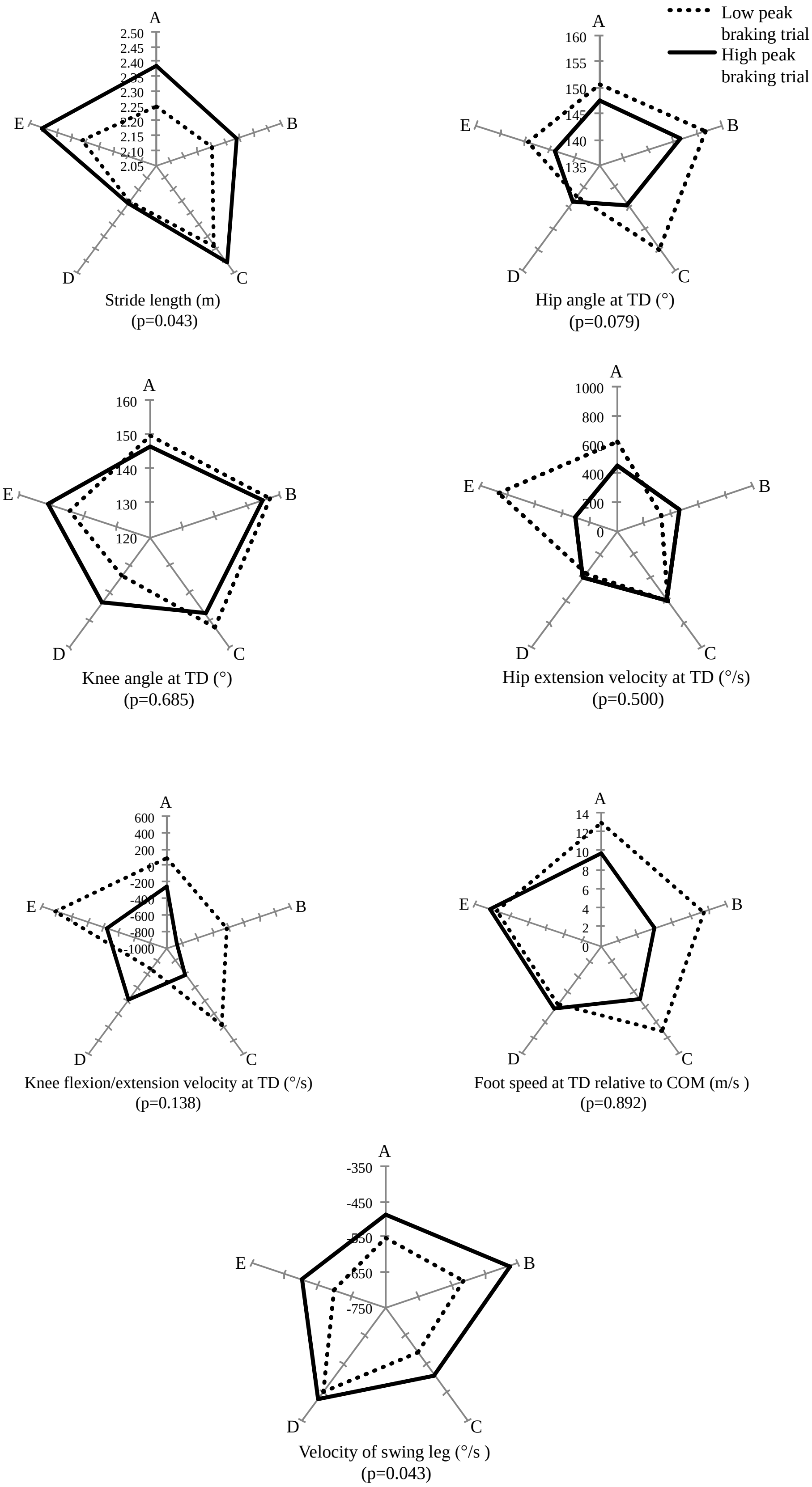


Figure 5-5 Radar plots of kinematic variables for a high peak braking and a low peak braking trial for 5 athletes (A-E). p-values are indicated on each plot.

The mean peak braking force for a high braking trial was -1.07BW and for a low braking trial was -0.71BW. This was significantly different (p=0.027) and represents a 40% difference. In Chapter 4 it was proposed there was a relationship between maximising step length by reaching forward with the foot at TD, but that it would incur a greater peak braking force. This is illustrated in the radar plot as significantly longer step lengths are observed for the high braking trial in comparison to the low braking trial (p=0.043). The average difference across the sample was 0.09m, however the plot indicates that there was only a 1cm difference for Athlete D suggesting other mechanisms are responsible the variance in braking force for this individual. As previously mentioned step length is dependent on the leg length of the individual, and therefore the hip and knee angles at TD are a more reliable measure by which to compare athletes. The hip angle at TD was significantly smaller (less extension) in the high braking trial (p=0.079) compared to the low braking trial. Subsequently in the high braking trial it illustrates the hip is extended less, and therefore likely contacting further away from the COM which increases the braking force. However developing braking force by extending stride length and reducing hip extension at touchdown will in turn increase the GCT (and thus reduce SF) and therefore the trade-off between these elements must be considered. Whilst not highlighted as a defining factor between elite and sub-elite athletes in Chapter 4 biomechanical principles denote that the degree of knee flexion at TD will influence the magnitude of the braking forces. A Wilcoxon signed ranks test indicated there was no significant difference in knee angle at TD between the high and low braking trials (p=0.685). Figure 5-7 illustrates the horizontal force curve for the entirety of the stance phase against the hip and knee joint angle profiles. Although a significant difference in knee angle at TD was not observed the plots illustrate that the knee is more flexed throughout the high braking trial. Thus although knee angle does not affect the peak braking force it appears to play a role in the overall braking impulse. Similarly the hip is more flexed in the high braking trial until the propulsive phase where there were no differences in hip angle. The graph illustrates the peak braking force is roughly equivalent to the time point where the hip and knee angles are identical (i.e. the lines of the graph cross). Therefore to delay the peak braking force athletes slow the rate of knee flexion (flatter line on the graph). This coincides with the findings of Chapter 4 that elite athletes minimise the knee flexion during stance. The angular velocity of the limbs at TD influences the speed of the limb relative to the speed of the COM and therefore the magnitude of the braking forces. There was no significant difference in the hip extension velocity at TD between the high and low braking trial (p=0.500). Chapter 4 illustrated that at the point of TD the knee has already begun the flexion phase and exhibits a flexion velocity at TD. There was no significant difference in the knee angular velocity at TD between the high and low peak braking trial (p=0.138). Interestingly the radar plot illustrates that the high braking trials were typified by flexion angular velocities, whilst the low braking trials were a mix of flexion and extension velocities. If the trials are studied on an individual basis it can be observed that in the trials with the higher peak braking forces the knee actually has a negative flexion velocity at the point of TD in contrast to an extension velocity. Figure 5-7 illustrates there were greater knee flexion velocities throughout stance for the high braking trial. The foot speed at TD has been identified in the literature as influencing the magnitude of braking forces. It is important to represent the foot speed relative to the velocity of the COM as it is the difference in magnitude between the velocities which will affect the magnitude of braking. There was a moderate positive correlation between the foot speed at TD and peak braking force (r=0.321), indicating a greater foot velocity at TD results in a smaller peak braking force as would be expected. The radar plot illustrates three of the athletes (A,B,C) had a considerably higher foot speed in the low peak braking trial. For athletes D and E the difference was minimal, however the difference in peak braking force between a low and high braking trial for three individuals was only 0.14 and 0.10BW respectively and therefore may not be large enough to ascertain a difference in foot speed. The final kinematic variable that has been linked to the magnitude of the braking force is the velocity of the swing leg at the point of TD. The velocity of the swinging leg impacts on the loading of the stance leg. There was a significant difference in the velocity of the swing leg between a high and low peak braking trial (p=0.043). The radar plot illustrates higher braking forces are observed when the velocity of the swing leg is lower, the mean difference across the sample was 80°/s, but again Athlete D displayed only a marginal difference compared to the other athletes (23°/s).

As discussed in Chapter 4 the horizontal component of force at maximal velocity has little relevance as the net horizontal impulse should be zero in order to maintain velocity. Therefore the vertical force component is of more interest, and specifically the vertical impulse which takes into account the time over which the force is applied (ground contact time). Whilst vertical impulse was not significantly correlated to horizontal velocity it displayed a strong correlation to SL (r=0.518) and SF (r=0.573), which as illustrated by the deterministic model are the two main components of horizontal velocity. The lack of significant difference to horizontal velocity as a whole was attributed to the individual difference in SL and SF reliance (Salo et al., 2011). There was a strong correlation between vertical impulse and flight time (r=0.642) which would be expected as based on the projectile motion equations flight time is in turn determined by the velocity at TO, and the vertical impulse during ground contact will determine the change in vertical velocity (impulse-momentum relationship). There was a weak correlation between ground contact time and vertical impulse (r=0.242). This implies it is potentially the force component of the vertical impulse which is of most importance. There was a strong correlation between vertical impulse and average Fz (r=0.731), peak Fz (r=0.539) and a moderate correlation to peak RFD (r=0.463). Interestingly there was also a moderate correlation between the vertical impulse and the peak braking force (r=0.438) and braking impulse (r=0.459), which suggests the respective components of force are interrelated.

As with the peak braking force the vertical impulse can be manipulated by the sprint kinematics. The relationship is not as straightforward as the peak braking force which occurs at one point in time as the vertical impulse is affected by the kinematics throughout the stance phase, along with the actions of the swing leg. In order to investigate the role of kinematics the trial with the lowest vertical impulse was compared to the trial with the highest vertical impulse for each of the five athletes. A Wilcoxon signed-ranks test was conducted between the key kinematics, and radar plots were constructed to show the differences between high and low vertical impulse trials and the individual differences across the sample (Figure 5-6). Further the GRF trace of a low and high vertical impulse trial are plotted against the hip and knee angles of the stance limb for the entirety of the stance phase (Figure 5-7).

There was no significant difference in the projection angle between the low vertical impulse trial in comparison to the high vertical impulse trial (p=0.224). The projection angle is dependent on the resultant vertical and horizontal GRF at the point of TO and it appears that in a high vertical impulse trial there is a greater influence of vertical force at the point of TO. However athletes B and E saw very little difference in projection angle between the low and high vertical impulse trials suggesting the impulse is influenced by another mechanism in these cases. The application of force at the point of TO will be influenced by the position of the COM at TO and the position of the lower limbs at TO. Both the hip and knee angles were more extended at TO in the low vertical impulse trials which was more pronounced at the knee joint (Figure 5-7). An increased leg extension force is associated with a flatter projection angle as the vertical component is retained at a sufficient magnitude whilst the larger remaining force is directed horizontally (Goodwin, 2011). The findings of Chapter 4 found that triple extension of the lower limbs at TO was disadvantageous as it lengthened the ground contact time. Thus it might be expected this triple extension would be associated with a higher vertical impulse due to the increase in time over which force can be applied. However these findings illustrate that the increase in ground contact time does not actually favour the stride as no extra vertical impulse is generated. Research shows that sprinters start reducing their force production once the support knee passes under the hip (Mann, 1985). This is illustrated on Figure 5-7 as the majority of vertical impulse is produced before the hip angle reaches 180° (at approximately 0.075s). Athletes should minimise the extension of the hip and knee at TO in order to maximise the vertical impulse and reduce the GCT. Chapter 4 also highlighted the importance of the swing leg due to the necessity to reposition the limbs quickly ready for the next ground contact. However it was also hypothesised that the action of the swinging leg may impact on the loading through the stance leg. A paired t-test between a high vertical impulse and low vertical impulse trial indicated that a high vertical impulse trial was typified by a smaller MHF angle (more flexion) of the swing leg, which was significantly different ($p=0.079$) to a low vertical impulse trial. Chapter 4 illustrated the joint angles at TO and the MHF angle are interrelated as minimising extension at TO allows athletes to begin the swing process earlier, and thus achieve a greater degree of maximum hip flexion, both of which are advantageous to vertical impulse production.

However whether vertical impulse is a positive or negative entity is yet to be proven. Mann and Herman (1985) found better sprinters had a lower vertical velocity and thus that too much vertical impulse is disadvantageous to performance. Too much vertical motion would increase the flight time and subsequently lead to a decrease in step frequency. Yet some element of vertical motion is needed in order to reposition the limbs ready for the ensuing ground contact phase. Thus it is hypothesised that the vertical impulse will be related to the velocity of the limbs in swing phase. A lower vertical impulse will necessitate a greater velocity of the limbs in the swing phase and vice versa. Due to the combination of flexion followed by extension velocities in the swing phase the average velocity was ignored and only the maximum flexion and extension velocities were considered. There was no significant difference in the maximum flexion and extension velocities of the hip and knee in the swing phase between a high and low vertical impulse trial. The radar plots indicate that for 4 out of the 5 athletes the maximum hip flexion and extension velocities were larger in the low vertical impulse trial (as hypothesised). Interestingly it was not the same athlete which displayed a lower velocity in the low vertical impulse trial for the flexion and extension phases. Athlete E had a considerably lower peak flexion velocity and a considerably higher peak extension velocity in the low vertical impulse trial compared to the rest of the sample. There appears to be no relationship between the vertical impulse and the maximum knee flexion velocity due to the variance across the sample and lack of uniformity in the radar plot. The role of the knee flexion velocity is to reach the maximum knee flexion velocity as quickly as possible. This has an indirect velocity on the velocity of the swing limb by reducing the moment of inertia of the swing leg which increase the angular velocity of the limb. In contrast to the hip joint the low vertical impulse trial appears to be typified by a smaller peak knee extension velocity. Knee extension only occurs in the late phase of swing and therefore the degree of extension velocity is likely to have little impact on the time taken for the swing phase in its entirety.

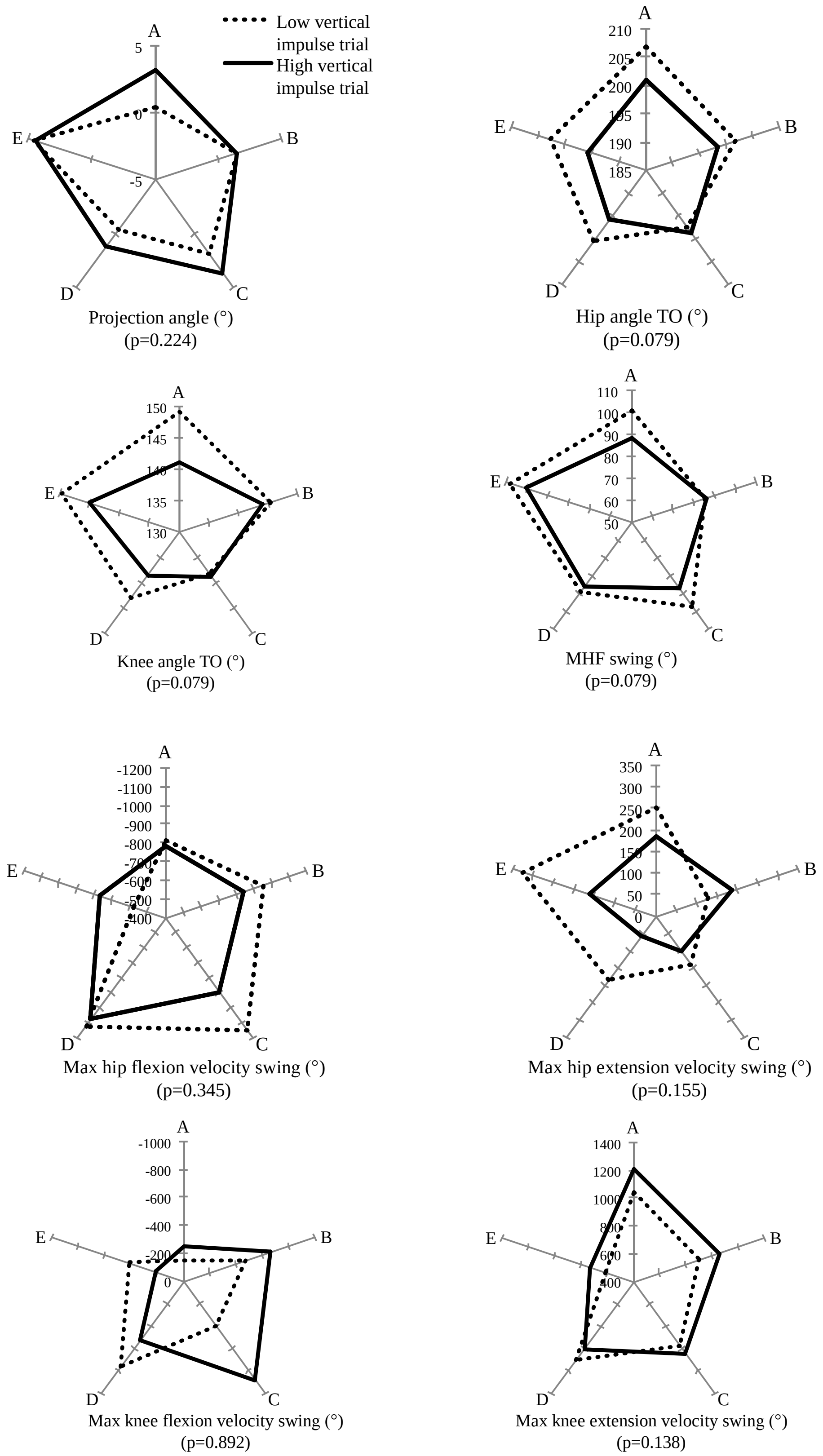


Figure 5-6 Radar plots of kinematic variables for a high vertical impulse and a low vertical impulse trial for 5 athletes (A-E). p-values are indicated on each plot.

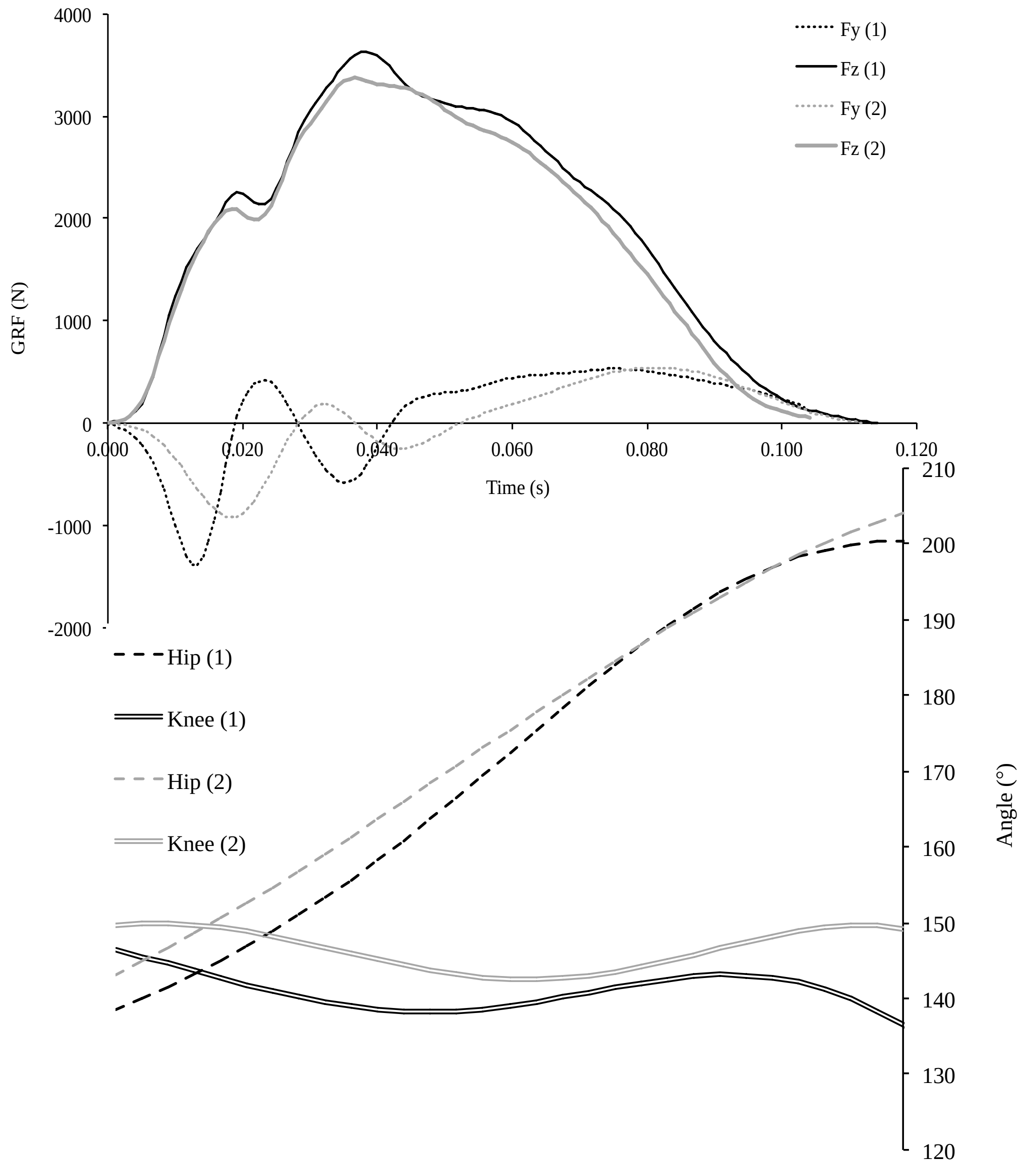


Figure 5-7 GRF trace and joint angle profile for a high braking and high vertical impulse (1) and a low braking and low vertical impulse (2) trial for athlete A

5.4 Conclusion

The kinetic analysis in this chapter provided a description of the external kinetics associated with velocities >9.0m/s for a sample of international-level athletes, including a trial at 11.26m/s. Figure 5-8 provides a graphical illustration of the main kinetic variables for sprint velocities exceeding 9.0m/s. Where sprint coaches have access to external kinetic variables this model can be used as a reference point of their athletes against true elite performers. The results indicated net horizontal impulse at maximal velocity is zero, and thus athletes should aim to minimise the braking impulse to negate the need for an equivalent propulsive impulse which would increase the GCT. Vertical impulse was strongly correlated to the SF, and thus athletes should generate sufficient vertical velocity to reposition the limbs in flight and prepare the limb for the subsequent touchdown phase. This can be achieved through the actions of the lower limb in the stance phase.

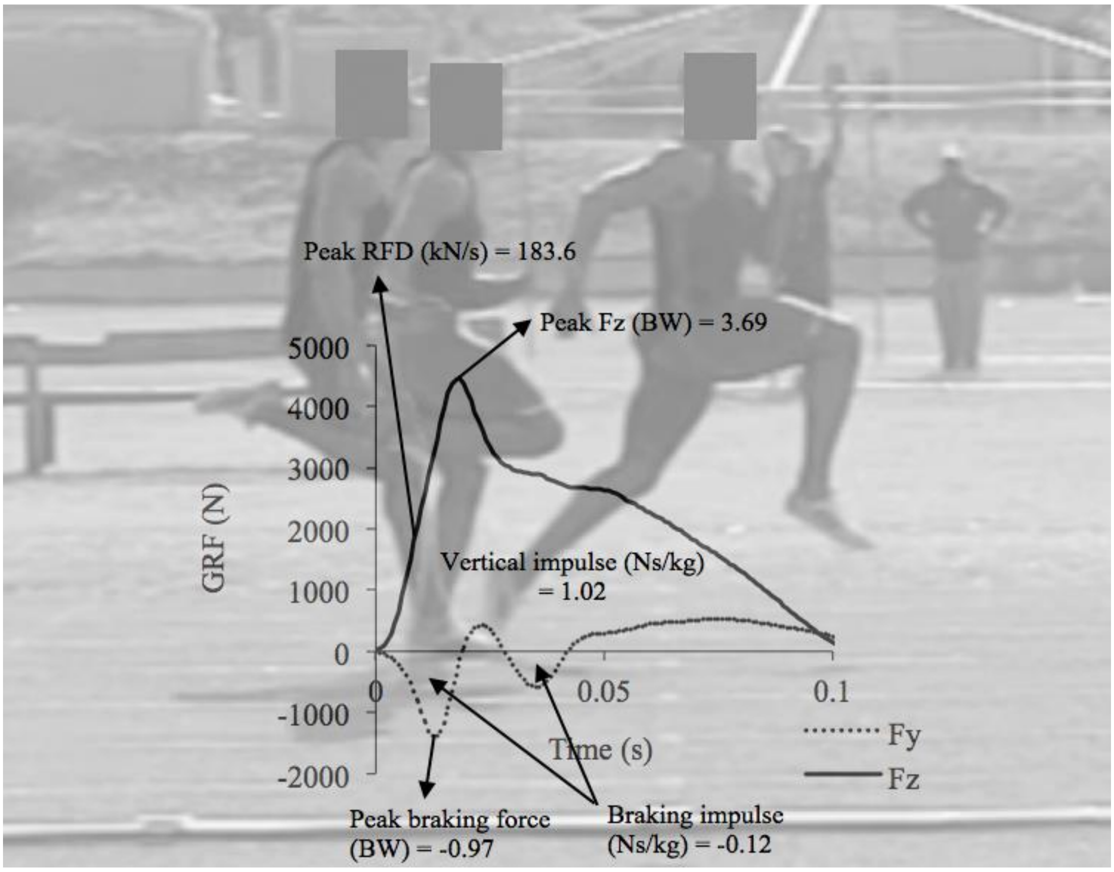


Figure 5-8 Kinetic model of maximal velocity sprinting (>9.0m/s)

The relationships between the kinetic and kinematic variables as discussed above can be used to confirm the hypotheses of the kinematic technical model outlined in Chapter 4. It was proposed elite athletes should maximise the hip angle at TD in order to minimise the TD distance, and subsequently the peak braking force. There was a strong correlation between hip angle and touchdown distance (r=-0.73), and hip angle was moderately correlated to peak braking force (r=0.313), thus confirming the hypothesis that a greater hip angle (i.e. more extension at TD) reduced the peak braking force. Minimising ground contact time is a function of increasing the stiffness of the leg, and more specifically the knee and ankle (Arampatzis, Bruggemann, & Metzler, 1999). This was confirmed as limiting the magnitude of knee and ankle flexion had a strong positive to correlation to GCT (0.514), indicating it is favourable to increase the stiffness of the stance limb and minimise flexion to maximise the step frequency. Furthermore limiting the flexion in stance reduces the distance the COM must travel during stance, indicated by a negative moderate correlation between MKF and stance distance (r=-0.327). This indicates the stiffness capabilities of the leg are critical to performance and thus training should be undertaken to enhance this. A potential indicator of an athlete's skill level is the ratio of contact time to stride distance, where a high ratio would indicate the hip function dominating over the capacity to generate stiffness at the knee and ankle (Goodwin, 2011). A novel finding of this thesis was the significance of the swing leg to elite sprint performance. Furthermore the current chapter has indicated the role of the swing leg on the development of vertical impulse. It was hypothesised that it is advantageous to have the swing leg further forward of the stance leg at both MS, and to maximise the degree of hip flexion in swing. A smaller degree of hip flexion in swing permitted a greater hip extension velocity in the late phase of swing (r=-0.437), and lead to greater extension of the leg at TD (r=0.311), which as aforementioned reduced the peak braking force.

5.5 Chapter summary

A kinetic analysis of sprinting was undertaken in order to further the understanding of how horizontal velocities >9.0m/s are achieved. The data provided is novel as no research to date has investigated the external kinetics at these velocities for over ground sprinting. Therefore the findings of this chapter address research question iii - *which kinetic variables are associated with elite levels of maximal velocity sprinting?* Furthermore the association between the kinetics and kinematics of maximal velocity sprinting lends insight into the GRF can be manipulated by sprint kinematics. This confirms the biomechanical principles proposed by the technical model developed in Chapter 4 and addresses the research question iv - *what are the relationships between the kinematics and kinetics of elite maximal velocity sprinting?* The kinematic and kinetic (Figure 5-8) technical models of elite maximal velocity sprinting have highlighted the key variables inherent to elite sprint performance. In order to achieve these variables proposed sprinters undergo periodised training programmes to develop both technique and strength. The findings of the earlier chapters provide a specification of kinematic and kinetic variables which should be targeted by training methods. It is a well-recognised principle of training that maximising the specificity of training augments the transference to the final skill. However existing research has failed to quantify the degree of specificity in the training methods undertaken by elite sprinters. Therefore the following chapter will aim to address research question *v. how can specificity be quantified holistically based on biomechanical movement principles?* and using this framework address research question *vi. what is the biomechanical specificity of training methods to maximal velocity sprinting?*

CHAPTER 6 – BIOMECHANICAL SPECIFICITY OF TRAINING

6.1 Introduction

The investigations in Chapters 4 and 5 identified the kinematic and kinetic parameters associated with elite maximal velocity sprint performance. A better understanding of the factors that limit performance at maximal velocity enables coaches to design training programmes to overcome these limitations. Training for both technique and strength cannot take place in isolation as changes in strength will likely lead to changes in technique, either intentionally or indirectly. It is well acknowledged that the transference of training to competitive performance is enhanced when training is specific to the end goal (Stone et al., 2000). Yet training specificity is often misinterpreted by coaches who focus on replicating the movement patterns of the skill, with no consideration to the speed, loading or coordination specificity (Graham-Smith et al., 2010). Therefore the initial aim of this study is to investigate how coaches interpret training specificity and subjectively assess specificity of common training methods for maximal velocity sprinting. A number of authors have aimed to develop a method to quantify specificity, however a limitation of such methods is that they fail to take into consideration the degree of importance of each element of specificity, for example are coordination or loading principles more relevant to the skill. Subsequently the second aim of this study was to develop a framework to quantify specificity holistically taking into consideration the speed, coordination, loading and balance principles as discussed earlier. Further to this the biomechanical specificity of select training methods undertaken by a group of elite sprinters will be investigated further. The training methods commonly adopted by elite sprinters can be divided into three key areas: plyometric exercises, strength training exercises and running drills.

Plyometrics are a common feature of sprint training due to the occurrence of a stretch-shortening cycle (SSC) which enhances the ability of the muscle-tendon unit to produce maximal force in a short period of time, such as in sprinting (de Villarreal, Requena, & Cronin, 2012). Therefore plyometric drills aim to target the GCT and RFD elements of the deterministic model. To optimise the transference to the sporting activity plyometrics should match the demands of the skill in question. Research tends to investigate the effect of plyometric training on sprint performance (Rimmer & Sleivert, 2000), rather than quantifying the specificity of these exercises to sprinting.

Strength training is used to improve both the force and power outputs required for sprinting, and therefore focuses on the force components which determine step length in the deterministic model. The most common approach to exercise prescription in strength training is based on the concept of specificity, which dictates that to achieve a specific performance enhancement athletes must perform training exercises at the specific load and velocity that best correspond to the muscular performance in the desired skill (Wilson, Newton, Murphy, & Humphries, 1993). The majority of specificity research focuses on the kinematic specificity (e.g. velocity specificity) of training methods with a disregard to the potential for kinetic specificity. Numerous kinematic evaluations of strength training exercises have been published, however kinetic evaluations of strength training are less available. Yet this research fails to quantify the similarity of strength exercises to sprinting, and where elite athletes are used they tend to be competitive weightlifters rather than track and field sprinters.

The rationale for the inclusion of running drills within a training programme is that the action of the drills are perceived to produce a movement pattern consistent with sprinting (Stokes, 1985). Drills can be adopted as part of the 'whole-part-whole' training method to practice specific aspects of maximal velocity sprinting technique. They typically relate to the step frequency component of the deterministic model as they aim to replicate the TD positions observed in sprinting and the angular velocities of the limbs. In the past training methods were evaluated by coaches using a trial and error method with their respective groups of athletes. Biomechanical advances now allow coaches to assess the effectiveness of a training method on a scientific basis, yet currently there is a lack of empirical evidence to support this method.

In order to address the research questions *v. – how can specificity be quantified holistically based on biomechanical movement principles?* and *vi. - What is the biomechanical specificity of training methods to maximal velocity sprinting?* The aim of the study was two fold; initially to develop a framework to quantify the specificity of sprint training methods, and secondly to provide a detailed analysis on the sprint training methods undertaken by a group of elite sprinters.

6.2 Quantifying biomechanical specificity

6.2.1 Introduction

A number of authors have aimed to develop a method to quantify specificity. Irwin and Kerwin (2005) ranked the similarity of drill progressions to the longswing in gymnastics using the root mean square difference (RMSD). The RMSD was represented as the ratio of the range of the variable to give a dimensionless value, and was combined with the variability score to give an overall score of specificity. Wilson et al. (2009) also used the RMSD to assess the difference in angular velocities between drills and the triple jump. The authors investigated each joint angle of each limb separately and then combined these to determine which drill had the highest specificity to the triple jump. The RMSD was used to assess the specificity of kinetics of a power clean to sprinting (Irwin et al., 2007). However a limitation of this is that it fails to take into consideration the degree of importance of each element of specificity. For example it does not account for whether it is more important for a skill to be specific from a kinematic or a kinetic perspective. A skill can be broken down into elements, and the significance of each of these elements to performance graded. Following this the level of a specificity of a training exercise can be quantified on each element separately, which then takes into consideration the importance of each element. Graham-Smith et al. (2010) stated that a skill should be specific with respect to speed, loading, movement coordination and balance principles, of which each can be broken down into more detailed elements. A similar process was described by Hughes and Franks (2007).

6.2.2 Methods

In order to quantify specificity holistically a skill can be broken down into the speed, loading, movement coordination and balance principles (Table 6-1), this will form the movement specificity framework (MSF) (Graham-Smith et al., 2010). From this the relative importance of each of these elements to the overall skill can be quantified on a grade from 0-2 where 0 is irrelevant, 1 is low and 2 is high. This determines the 'importance rating'. Following this the degree of association of each movement principle between a given training method and the skill is rated from 0-3 where 0 is no association/irrelevant, 1 is low, 2 is moderate and 3 is high. This determines the 'association rating'. The importance rating and the association rating are multiplied to give an overall specificity score for each movement principle. To work out the movement specificity ratio (MSR) the maximum available score for the skill is calculated as the sum of the importance ratings multiplied by 3 (the highest grade of association). Then the sum of the individual movement principles scores is divided by the maximum available score to give a MSR (Equation 5). This has previously been presented at BASES workshops in 2008 and 2009 by Graham-Smith, Jones, Comfort, and Matthews (2008). For the purpose of this thesis it has been modified to maximise its application to sprint training methods, for example defining the magnitude of load as 'similar to or greater than' to allow for the principle of overload of training, and assigning a score for cyclical movements which correspond to those of maximal velocity sprinting. An example of the MSR calculation for a Bulgarian split squat is provided in the Appendix.

$$\text{MSR} = \left(\frac{\sum n\ (importance\ rating\ x\ association\ rating)}{maximum\ available\ score}\right)$$

Equation 5 Movement specificity ratio (MSR) calculation

In order to validate the MSF a sample of seven strength and conditioning coaches from both the English Institute of Sport and Aspire Sports Academy (Doha, Qatar) were recruited for the study. All had experience working with elite track and field athletes and had been strength and conditioning coaches for an average of 12 years. Firstly the coaches were asked to subjectively rank eight common strength and conditioning exercises based on their degree of specificity to maximal velocity sprinting, where 1 was the most specific and 8 was the least specific. The exercises selected were resisted (weighted vest) sprinting, supramaximal (towing) sprinting, power clean, deadlift, snatch, single leg squat drop, countermovement jump and rebound jump. These exercises were selected based on their prevalence in the training programmes of elite sprinters. The results of the subjective ranking are provided in

Table 6-2. Following this the coaches were presented with the MSF and were asked to assign an association rating between each of the strength exercises and maximal velocity sprinting for each of the movement principles listed in Table 6-1. From this a total MSR was calculated for each strength exercise for each coach. The results of this are presented in Table 6-3. Using the calculated MSR's the exercises were re-ranked from 1 to 8, and Spearman's rank order correlation co-efficients (ρ) were calculated to see if there was a change in the rank pre and post the use of the MSF.

Table 6-1 Description of movement principles included in MSF

MOVEMENT PRINCIPLES	
Speed Principles	
Whole Body Speed	Is the exercise similar with respect to horizontal speed? Is the exercise similar with respect to vertical speed? Is the exercise similar with respect to rotation speed
Contact / Movement time	Is the exercise similar with respect to time in contact with the ground or execution time?
Loading Principles	
Type of loading	Force Acceptance (eccentric muscle contraction following impact) Force Acceptance (eccentric muscle contraction without impact) Force Generation (active isometric muscle contraction) Force Generation (active concentric muscle contraction)
Magnitude of Load	Does the exercise elicit similar or greater vertical ground reaction forces? Does the exercise elicit similar or greater horizontal ground reaction forces?
Rate of Loading	Is the rate of loading similar in force acceptance? Is the rate of force development similar?
Movement Coordination Principles	
Force - Length	Do the joints go through similar ranges of motion?
Force - Velocity	Do the joints move at similar angular velocities?
Stretch-Shorten Cycle	Do the muscles crossing joints undergo a stretch-shortening cycle?
Symmetry	Is the movement unilateral or bilateral?
Sequential movements	Does the movement involve a kinetic chain from proximal to distal segments?
Muscle Relaxation	Is the skill a cyclical movement? If Yes, does the movement help to relax antagonists when agonists are working?
Balance Principles	
Support / Balance	Does the exercise challenge proprioception and balance for control?
Muscle Balance	Does the exercise help to address balance between agonist and antagonist muscle groups?

6.2.3 Results

The initial ranking of the eight exercises is provided in Table 6-2. No two coaches ranked the exercises in the same order which supports the theory that the concept of training specificity is misunderstood and requires further clarification. All coaches agreed resisted and supramaximal sprinting were the most specific to maximal velocity sprinting (scoring either 1 or 2), however there was disparity as to whether resisted or supramaximal was most specific. Following this coaches tended to agree the plyometric exercises (countermovement and rebound jump) were the next most specific, yet the ranking for CMJ ranged from 4-8 indicating disagreement between coaches regarding its degree of specificity. The Bulgarian split squat also showed a large range across coaches and had the largest standard deviation across all exercises. All coaches agreed the deadlift was amongst the lowest with respect to specificity to maximal velocity sprinting.

Table 6-2 Subjective ranking of eight strength exercises between coaches where 1 indicates the most specific and 8 is the least specific to maximal sprinting

	Coach								
	A	B	C	D	E	F	G	*Mean*	*SD*
Resisted sprinting	1	2	1	2	1	1	1	*1.29*	*0.49*
Supramaximal sprinting	2	1	1	1	2	1	1	*1.29*	*0.49*
Power clean	5	5	6	3	6	6	5	*5.14*	*1.07*
Deadlift	7	7	8	8	8	8	7	*7.57*	*0.53*
Snatch	6	6	7	4	7	7	6	*6.14*	*1.07*
Bulgarian split squat drop	3	8	5	7	5	5	8	*5.86*	*1.86*
Countermovement jump	8	4	4	6	4	4	4	*4.86*	*1.57*
Rebound jump	4	3	3	5	3	3	3	*3.43*	*0.79*

Following the subjective ranking the coaches were asked to assess each exercise using the MSF and from this an overall MSR was calculated for each exercise (Table 6-3). Using the total MSR's from each coach the exercises were re-ranked from 1 to 8 and the results presented in Table 6-5.

Table 6-3 Movement specificity ratio (MSR) of each strength exercise for each coach

	Coach								
	A	B	C	D	E	F	G	*Mean*	*SD*
Resisted sprinting	0.94	0.89	0.95	0.96	0.93	0.94	0.93	*0.93*	*0.02*
Supramaximal sprinting	0.82	0.93	0.95	0.97	0.86	0.94	0.93	*0.91*	*0.05*
Power clean	0.39	0.41	0.37	0.42	0.45	0.43	0.41	*0.41*	*0.03*
Deadlift	0.25	0.26	0.18	0.24	0.22	0.25	0.26	*0.24*	*0.03*
Snatch	0.33	0.39	0.31	0.39	0.34	0.37	0.39	*0.36*	*0.03*
Bulgarian split squat drop	0.48	0.46	0.38	0.50	0.48	0.51	0.50	*0.47*	*0.04*
Countermovement jump	0.42	0.45	0.45	0.43	0.46	0.45	0.45	*0.45*	*0.01*
Rebound jump	0.57	0.56	0.56	0.54	0.59	0.57	0.57	*0.56*	*0.02*

The MSF illustrates that based on movement principles the most specific training methods to maximal velocity sprinting are resisted (MSR=0.93) and supramaximal (MSR=0.91) sprinting. This would be expected as these are the exercises which most closely replicate the action of sprinting. Furthermore resisted sprinting exerts overload on the athlete which increases its specificity. Both the CMJ and rebound jump incorporate a SSC phase and thus display a moderate degree of specificity to sprinting. The rebound jump displayed a greater degree of specificity (MSR=0.56) to sprinting than the CMJ (MSR=0.45) as the impact phase followed by a take-off phase replicates the ground contact phase of maximal velocity sprinting, and thus the rebound jump displays high specificity with respect to the loading principles. The specificity of the CMJ can be enhanced if the downward phase of the CMJ is controlled so the exercise imitates the joint range of motion and angular velocities of maximal sprinting. Single-leg squats were classified as displaying 'medium specificity' to maximal sprinting by Young et al. (2001a). Based on the MSR the most specific strength training exercise to maximum velocity sprinting was the Bulgarian split squat (MSR=0.47). This can be attributed to its unilateral nature and the range of motion of the lower limb joints which mirror the ground contact phase of sprinting. The power clean was assigned an MSR of 0.41 which is the second highest of the strength exercises. Based on the dominant role of hip kinetics in successful sprinting the power clean should elicit similar kinematic and kinetic characteristics (Irwin et al., 2007). To the authors knowledge the power clean is the only strength exercise for which its specificity to maximal sprinting has been quantified. Tricoli et al. (2005) reported similar GRF profiles between the power clean and 10m sprinting, whilst Okanda et al. (2005) concluded the power outputs from a power clean were highly correlated to the lower limb angular kinematics in sprinting. Irwin et al. (2007) found peak hip kinetics were considerably higher in the power clean than sprinting, and thus implemented the overload training principle. When plotted against hip angle it was shown the power clean was more closely associated with the acceleration phase of the sprint than the maximal velocity phase. The power clean displays specificity in the loading principles, but lacks specificity with regards to the movement coordination principles. Based on movement principles the snatch achieved a MSR of 0.36. The snatch is a bilateral exercise and therefore lacks specificity with regard to symmetry, however the motion of picking a bar off the ground and extending through the hip, knee and ankle means the joints go through a similar range of motion to sprinting (Harbili, 2012). The deadlift was the lowest ranked strength exercise to maximal sprinting with an MSR score of 0.24. This coincides with Young, McDowell, and Scarlett (2001b) who classified the deadlift as a 'nonspecific' exercise for maximum speed sprinting. This would be expected as the deadlift is more commonly used as a training exercise for the acceleration phase, and therefore has a place within a periodised training programme of elite athletes. As the deadlift was performed throughout the season in the current group of elite sprinters it will be investigated further to establish potential kinematic and kinetic variables which may display some similarity to the maximal velocity phase.

Table 6-4 Objective ranking (following the use of the MSF) of eight strength exercises between coaches where 1 indicates the most specific and 8 is the least specific to maximal sprinting. Spearman's rank was calculated between the coaches subjective (pre-MSF) and objective (post-MSF) ranking

	Coach								
	A	B	C	D	E	F	G	*Mean*	*SD*
Resisted sprinting	1	2	1	2	1	1	1	*1.29*	*0.49*
Supramaximal sprinting	2	1	1	1	2	1	1	*1.29*	*0.49*
Power clean	6	6	6	6	6	6	6	*6.00*	*0.00*
Deadlift	8	8	8	8	8	8	8	*8.00*	*0.00*
Snatch	7	7	7	7	7	7	7	*7.00*	*0.00*
Bulgarian split squat drop	4	4	5	4	5	4	4	*4.14*	*0.38*
Countermovement jump	5	5	4	5	4	5	5	*4.86*	*0.38*
Rebound jump	3	3	3	3	3	3	3	*3.00*	*0.00*
Spearman's rank (ρ) between pre and post MSR	0.83	0.76	1.00	0.62	0.98	0.98	0.79	*0.85*	*0.14*

Following the use of the MSF there was more agreement amongst coaches regarding the order of ranking of the exercises, with coaches only disagreeing on the order of specificity between the assisted and supramaximal sprinting and the Bulgarian split squat and countermovement jump. The average Spearman's rank order correlation across the sample between pre and post MSF was 0.85, which ranged from 0.62 for coach D to 1.00 for coach C. This indicates that for coach C the use of the framework did not change their ranking of the exercises, whilst for coach D the use of the framework changed their ranking for 4 of the 8 exercises with the Bulgarian split squat changing from the 7th most specific to the 4th most specific following the use of the MSF.

6.2.4 Discussion

Developing a framework for specificity facilitated coaches to consider specificity with respect to speed, loading, coordination and balance principles as opposed to just considering the movement patterns alone. Following the use of the framework there was a good agreement between coaches for the total MSR scores of each exercise, and thus the ranking order of exercises with respect to specificity was similar. Using the MSR values the exercises were re-ranked to see how these compared to the coaches original subjective ranking. For five out of the seven coaches the MSF changed their ranking order of the exercises. This indicates that in the subjective ranking coaches are potentially failing to consider all elements of specificity. Unsurprisingly the resisted and supramaximal sprinting were still ranked highest amongst the exercises. Based on the average MSR scores the most specific resistance training exercises to maximal sprinting was the Bulgarian split squat (MSR=0.47). However there was still variance between coaches regarding its rank of specificity in comparison to other exercises, and thus it will be investigated further in a sample of elite athletes. The deadlift was ranked the lowest of the eight exercises and thus its specificity to maximal sprinting appears to be limited, although its role as an exercise for the acceleration phase of sprinting is well recognised. Therefore the deadlift will be also investigated in a sample of elite athletes to establish whether it is specific to any speed, loading, coordination or balance principles of maximal velocity sprinting.

6.3 Biomechanical specificity of training methods

6.3.1 Introduction

The MSR values presented in Table 6-3 reveal variance in coach's subjective opinion of the specificity of training methods for maximal velocity sprinting. Particularly there was discrepancy in the MSR value of the Bulgarian split squat which ranged from 0.38 to 0.51, and in the deadlift which ranged from 0.18 to 0.36. The deadlift was the lowest ranked exercise and thus its inclusion in the training programme of elite sprinters could be questioned. Subsequently these two exercises were investigated further in a group of elite sprinters in order to answer research question *vi - what is the biomechanical specificity of training methods to maximal velocity sprinting?*

Strength exercises are used to develop the maximal strength and power of the athletes to maximise the ability to develop force over the short ground contact time. Therefore strength exercises represent training focused on the stance leg of the gait cycle. Squatting with a mass on the shoulders is one of the most widely used training exercises for the development of strength in the lower leg extensor muscles (McLaughlin, Dillman, & Lardner, 1977). In the interest of maintaining specificity to the skill in question the squat is often performed unilaterally to reflect the unilateral nature of sprinting. Performance in sprinting is dependent on the ability to resist large ground reaction forces during landing in the eccentric phase (McNittgray, 1993). In order to replicate this in strength training the single-leg squat is sometimes performed with the rear leg raised (Bulgarian split squat) and the athlete 'drops' into it with the aim of mimicking the touchdown phase of sprinting. This is termed a Bulgarian split squat drop (BSq_{drop}). However whether the kinematics and kinetics of the BSq_{drop} reflect those of maximal velocity sprinting is yet to be established. In the early phases of a periodised training programme an athlete must develop maximum strength before shifting to developing power and increasing the maximum rate of force development. Research has supported a significant relationship between maximum leg strength and sprinting speed (Baker & Nance, 1999), and thus the deadlift has a role within a periodised training programme. As a training programme progresses the focus moves from more general strength exercises to specific strength exercises Young et al. (2001b). Yet commonly the deadlift is still employed throughout the training season and therefore its biomechanical profile must be established. A number of studies have reported the kinematics of the deadlift (McGuigan and Wilson (1996); Escamilla et al. (2000); Hales, Johnson, and Johnson (2009)), however differences in the skill level of subjects and the load lifted limit comparisons across studies. To the authors knowledge the only study to date to investigate the kinetics of the deadlift was conducted by Fauth et al. (2010), however the analysis was limited to peak GRF and RFD with no reference to additional variables.

Further to strength exercises elite sprinters perform running drills in the majority of training sessions. The rationale for the inclusion of running drills within a training programme is that the action of the drills are perceived to produce a movement pattern consistent with sprinting (Stokes, 1985), but whether this is achieved has not yet been scientifically investigated. Running drills were used at the start of each training session to target the late swing phase of the gait cycle and the TD position of maximal velocity sprinting, and therefore are representative of a training exercise focusing on the swing phase. The running drills selected for detailed analysis were the A skip, B skip and scissor drill. These drills were selected based on their regularity in the training programme of an elite group of sprinters and their perceived specificity to the swing phase of maximal velocity sprinting.

A detailed biomechanical analysis was conducted on the above training methods, and their specificity to maximal velocity sprinting will be discussed based on the speed, loading, coordination and balance principles outlined in Table 6-1.

6.3.2 Methods

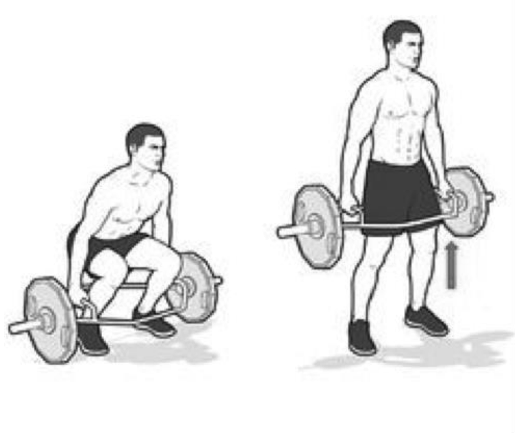
Six international-level male sprinters provided written consent for data to be collected at their training sessions. The subjects were all members of the same sprint training group based at Lee Valley Athletics Centre and were coached by a UK Athletics accredited coach. Basic anthropometric measurements along with their 100m personal best times are listed in Table 5-1. Data collection did not involve any invasive procedures (as was the case for all studies presented in the thesis) and was approved by the University of Salford Ethics Committee. Data collections were carried out between November 2011 and June 2012 in the year leading up to the London 2012 Olympic Games. All athletes were injury free at the time of commencement of data collection. Data were collected at the Lee Valley Athletics Centre either on the indoor or outdoor track based on the discretion of the coach.

In order to establish the specificity of training methods it was necessary obtain kinematic and kinetic data of each of the athletes maximal velocity sprinting. The criteria for a training session in which data of maximal velocity sprinting could be collected was a session in which athletes were instructed to run maximally over a distance of 65m or longer in a straight line. This was obtained during the data collection sessions for Chapter 5. Over the course of the training season kinematic data were collected for each athlete on six separate occasions.

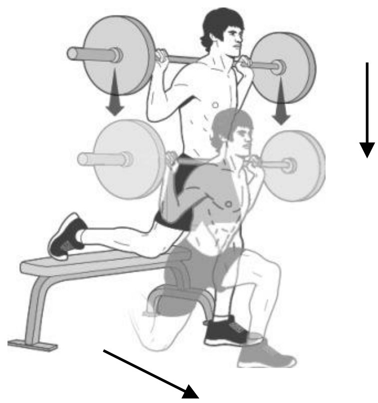
The two strength training exercises that were a consistent part of the strength training programme of all six athletes were BSq_{drop} and deadlifts. A description of the lifts is provided in Table 6-5 and an illustration is provided in Figure 6-1.

Table 6-5 Description of execution of the deadlift and BSq_{drop}

Lift	Description
Bulgarian split squat drop (BSq_{drop})	Stand with barbell on shoulders feet shoulder width apart. Rear foot raised on bench 30cm high and 50cm back. Then 'drop' into the lunge position (front foot landing on force plate). Control the movement at the parallel thigh position and hold until steady.
Deadlift	Trap bar. Feet shoulder width apart under the bar, hand grip slightly wider than the feet. Lower hips so thighs are parallel to the floor and straighten back. Stand up by raising hips and shoulders at the same rate and maintaining a flat back, lifting the bar vertically and close to the body.



a)



b)

Figure 6-1 Illustration of a) trap bar deadlift and b) BSq_{drop}

Data collection sessions were designed to coincide with the training schedule, and were non-obtrusive in order to maintain external validity. The experimental set-up remained the same regardless of the lift being analysed. To obtain ground reaction force data a Kistler force plate (0.60 x 0.40 x 0.03m) (Kistler Instruments 9287BA, Switzerland) was placed in the centre of an existing lifting platform in the gym, and surrounded by a custom-made wooden surround (1.32 x 1.23 x 0.03m) so the force plate was flush with the lifting platform. The force plate was connected to a personal laptop and data were sampled at 1200Hz. To obtain sagittal plane kinematic data two high-speed (CASIO Exilim F1) cameras were placed either side of the lifting platform. To ensure the hip, knee and ankle joints were unobstructed from view throughout the lift the cameras were placed at 18° to the perpendicular so the weights on the barbell did not obstruct the view (Figure 6-2). This method has been adopted by both Escamilla, Lowry, Osbahr, and Speer (2001) and Canavan, Garrett, and Armstrong (1996). Due to the low lighting conditions in the gymnasium at Lee Valley Athletics Centre two additional floodlights were erected at the edge of the lifting platform (but as not to obstruct the athlete or the cameras) to provide sufficient light conditions for the high-speed video. When the athlete was ready to perform the lift the researcher triggered the force plate to record a zero reading and then the athlete was informed to step on the plate. The force plate was set to a default sampling time dependent on the type of lift being performed (range 10 – 40 seconds). The athlete could then perform the lift with no further intrusion from the researcher.

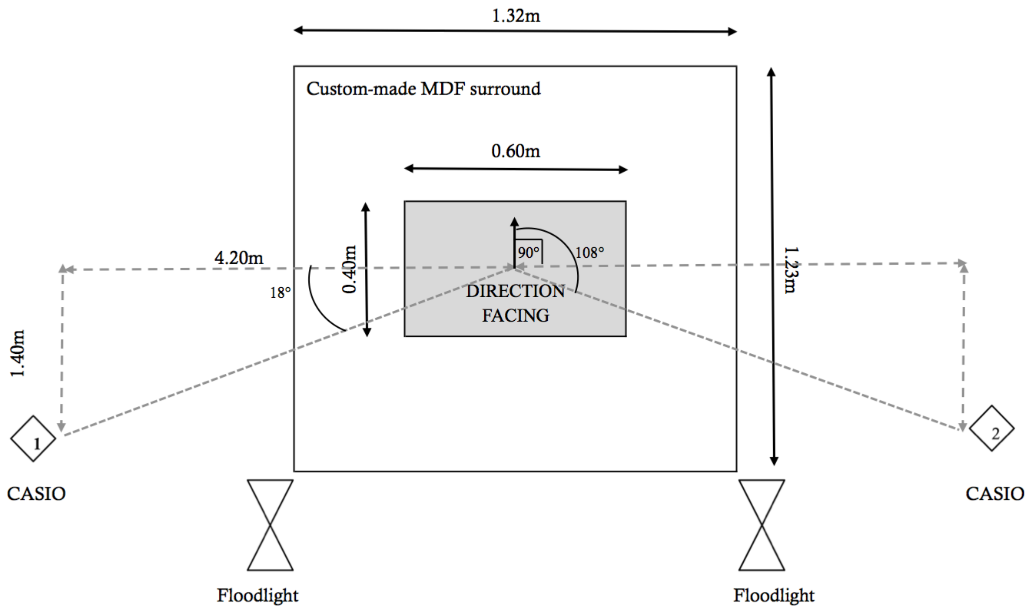


Figure 6-2 Strength and conditioning biomechanical specificity experimental set-up

Prior to testing all subjects performed an individual warm-up of the lift by building up progressively with load until they reached the load in question to be analysed. The load, number of repetitions and number of sets was dictated by the coach and thus out of control of the researcher. Where possible the researcher selected similar protocols between athletes for analysis. Where more than one set of an exercise was performed the analysis was performed on the first set to avoid the influence of fatigue. Three consecutive repetitions were selected for analysis for each lift. For the single-leg squat three consecutive repetitions on each leg were selected.

Details of the athlete's weight, bar weight and overall system load (SLd) (subject weight + bar weight) for each athlete for each type of lift are presented in Table 6-6. The deadlift and BSq_{drop} loads are also represented as a percentage of each individual's 1RM for the deadlift and back squat, respectively. In addition their average weight from the kinetic analysis of maximal sprinting is included.

Table 6-6 Athlete weight, bar weights, system loads across testing sessions

	Deadlift				BSq_{drop}				Sprinting
	Weight (N)	Bar (kg)	%1RM	SLd (N)	Weight (N)	Bar (kg)	%1RM	SLd (N)	Weight (N)
A	915	250	86	3367	922	50	36	1413	920
B	847	200	75	2809	844	50	35	1335	840
C	983	250	83	3435	987	50	42	1478	989
D	731	150	60	2203	732	50	38	1222	723
E	899	200	83	2861	896	40	44	1288	895
F	825	190	82	2689	838	65	46	1476	816

Kinetic data was collected with Bioware software and analysed within the software. As the focus of the lift is vertical ground reaction force only Fz was selected for subsequent analysis. For the deadlift only the concentric phase of the lift was of interest, beginning with the lifting of the weight from the ground until the end of the movement (full extension of the knees and hips). For the BSq_{drop} only the eccentric phase was of interest, from the point of TD until stabilisation. The instant of TD was defined as the first time point when Fz exceeded the threshold value. The contact threshold was defined as the mean value plus two standard deviations of the unloaded force plate as used in previous studies (Bezodis et al. (2008); Exell (2010)). This threshold value was chosen as it represents 95% of the area under a normal curve, therefore giving 95% confidence in the detection of TD and TO (Vincent & Weir, 2012).

Based on the guidance of the findings in Chapter 4 and 5 and current literature the following variables were calculated for each of the lifts: time, average Fz, vertical impulse, peak Fz, time to peak Fz, average force over a period of 100ms and peak RFD. In addition for BSq_{drop} the instantaneous eccentric rate of force development (E-RFD) was identified from the point of TD. The reliability of the kinematic and kinetic variables has previously been established in Chapter 3 and Chapter 5 respectively.

As detailed in Chapter 4 the raw videos were imported into the digitising software (Quintic Biomechanics Version 20). As a full COM profile is not of interest in this chapter the manual digitisation was narrowed to five anatomical points and was repeated for each side of the body. The digitised points were the 5th metatarsal joint, lateral malleolus, lateral epicondyle, greater trochanter of the femur and the greater tuberosity of the humerus. The first digitisation frame was identified as the frame number occurring 30 frames prior to the first movement. The subsequent frames were then digitised at 300fps until 30 frames after the lift was completed (based on instruction of the coach).

Once digitisation was completed the raw coordinates were exported to an Excel file and all further analysis was done using a bespoke spreadsheet. The horizontal and vertical scale factors calculated from the calibration frame were applied to scale the raw digitised coordinates and to obtain absolute displacement time-histories. To account for the effect of the camera angle (in relation to the perpendicular) on subsequent joint angles the *x*-coordinates of the hip, knee and ankle joint centres were corrected using the method detailed below and illustrated in Figure 6-3. The method assumes the proximal and distal joints remain in the same position, and subsequently the vertex between these joints remains constant, along with the segment lengths. The joint of interest is modified based on the rotation about the axis of the vertex joining the proximal and distance joints.

Firstly the distance (d) between the original joint centre (B) and the vertex between the proximal and distance joint centres (c) was calculated using Equation 6 where (γ) is the angle between the proximal segment and vertex between the proximal and distal joint centres.

$$d = \sin(\lambda) * a$$

Equation 6 Calculation of distance from joint centre to vertex between proximal and distal joints

Secondly the distance (S) between the amended joint centre (B1) and the vertex (c) was then calculated based on the original distance divided by the cosine of the camera angle used (in this case 18) (Equation 7).

$$s = \frac{d}{(\cos \alpha)}$$

Equation 7 Distance from amended joint centre to vertex between proximal and distal joints

Using this modified distance the *x*-coordinate of the modified joint centre can be calculated by summing the original *x*-coordinate (B) with the difference between the distance to vertex lines.

$$B_x^1 = B_x \pm (S - d)$$

Equation 8 Calculation of modified x-coordinate

The modified *x*-coordinate and the original *y*-coordinate were then used to calculate the modified joint angle for use throughout the rest of the chapter.

Data were filtered using a low-pass Butterworth filter (Winter, 1990) with a cut-off frequency of 11Hz. This cut-off was selected to maintain consistency with the cut-off frequency used for the kinematics of sprinting. As strength training is performed slower than sprinting a higher cut-off frequency than perhaps necessary will be not be disadvantageous as there is likely to be less higher frequency noise. All filtered displacement data were combined with segmental inertial data (de Leva, 1996) in order to create a 4-segment model (trunk, thigh, shank and feet). Trunk, hip, knee and ankle angles were calculated using the definitions detailed in Figure 4-4. Linear and angular displacement time histories then underwent second central difference calculations to derive the corresponding velocity and acceleration values. Where appropriate joint angles and angular velocities were identified at key events to correspond with key events in sprinting. In other cases the maximum, minimum and range of joint angles were investigated, along with peak and average joint angular velocities, to correspond with those identified during maximal velocity sprinting.

Data were tested for normality using the Shapiro-Wilk test. A non-significant result indicated the data was distributed normally and therefore a parametric test could be used to test for significant differences. Multiple paired samples t-tests were used to compare the kinematics of the deadlift and BSq_{drop} to maximal velocity sprinting. Paired samples t-tests were used to compare the GRF variables of the deadlift and BSq_{drop} to maximal velocity sprinting. Statistical significance was set at $p<0.05$. Data were analysed using the statistical package SPSS (Version 20.0).

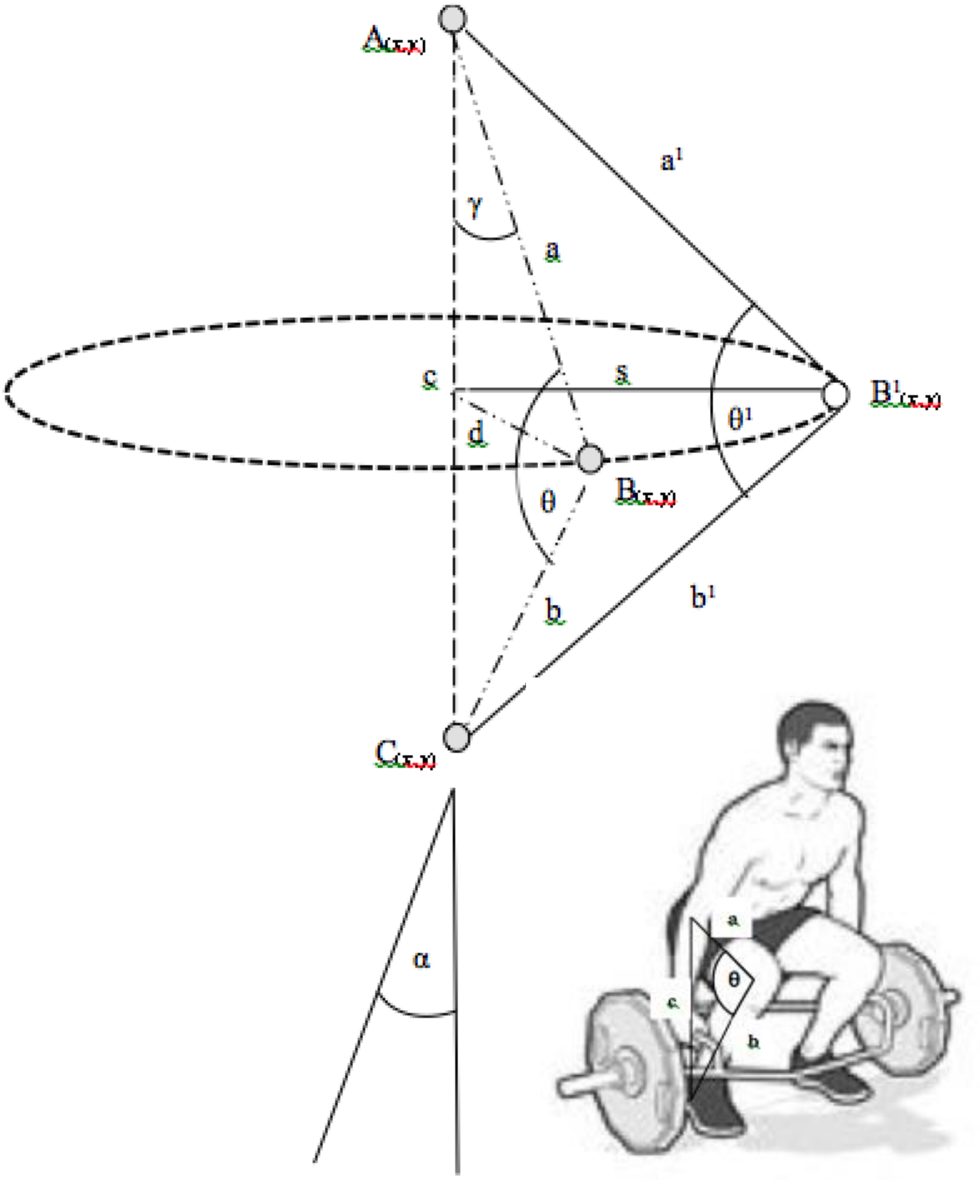


Figure 6-3 Calculation of joint angles from amended camera position

a	Distal segment length
b	Proximal segment length
d	Distance from joint centre to vertex between proximal and distal joint centres
θ	Original joint angle
a^1	Modified distal segment length
b^1	Modified proximal segment length
s	Distance from new joint centre to vertex between proximal and distal joint centres
θ^1	Modified joint angle
α	Camera angle (from the perpendicular)
γ	Angle between proximal segment and vertex between proximal and distal joint centres
A	Proximal joint centre
B	Mid-joint centre
C	Distal joint centre
B^1	Modified mid-joint centre

As the purpose of running drills is to replicate the movement patterns in maximal sprinting the kinematic data is of most relevance, therefore a kinetic comparison of running drills was not undertaken.

The running drills selected for inclusion in the current study were the A skip, B skip and scissor kick. These drills were selected based on their perceived objective to replicate elements of sprint technique, along with their regularity within the training programmes of elite athletes. A brief description of how each drill is performed is provided below.

The focus of the A skip is the knee lift. The legs alternate with one leg supporting and the opposite leg driving to a position of hip flexion (bringing the thigh to the horizontal) with the knee flexed. In this position the ankle should be dorsiflexed. The hip and knee then rapidly extend simultaneously towards the ground, with the ankle remaining in a dorsiflexed position. The mechanics of the upper body should resemble the sprinting action with a slight forward lean. The arms should exhibit a vigorous arm action in order the balance the leg action. The 'skip' action requires that the knee lift in the swing leg occurs over the period of 2 ground contacts of the stance leg, as illustrated in Figure 6-4 (for the right leg). As the focus of the A skip is the knee lift the approximate point of the high knee position (i.e. maximum hip flexion) is indicated on the diagram (MHF).

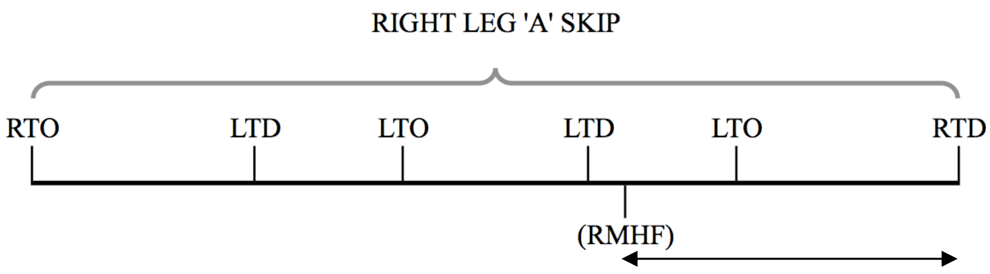


Figure 6-4 Right A skip drill technique (order of ground contacts)

Figure 6-5 Diagrammatic example of the A skip drill

The mechanics of the B skip are similar to the A skip except for the knee kinematics in swing (Figure 6-6). The focus of the ‘B’ drill is the foreleg reach. Here instead of hip and knee extension occurring simultaneously to bring the foot underneath the body, the initial action is the extension of the knee, followed by hip extension. The resulting path of the foot is in a circular position from the front of the body to contacting underneath the body. Ground contact occurs slightly in front of the centre of mass (as within sprinting). The B skip is also conducted in a skipping fashion as described for the A skip.

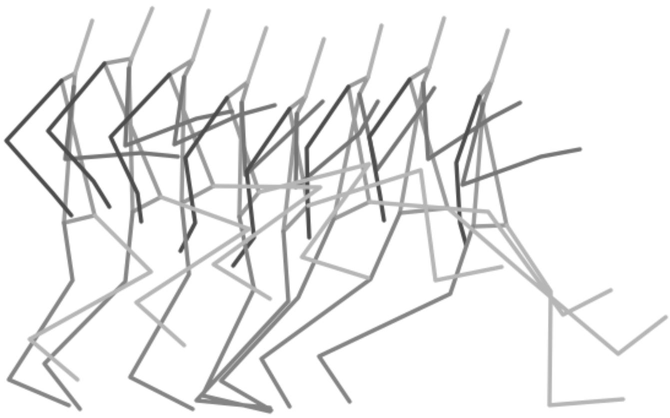


Figure 6-6 Diagrammatic example of B skip drill

Where the A and B skip are performed in a skipping motion, the scissor (or ‘straight-leg bound’) drill is performed with alternate ground contacts. The focus of the scissor drill is the extension of the hip and foot speed approaching ground contact. The knee angle remains ‘locked’ in an extended position (approx. 140°) throughout the drill. This exercise is designed to isolate and emphasise the forward displacement of the hips (Brady & Maraj, 1999).

Figure 6-7 Diagrammatic example of the scissor drill

Collection of kinematic data of the running drills was collected at the start of the training season on the indoor track. One lane of the indoor running track was designated for the analysis. In order to obtain sagittal data for the running drills one high-speed camera (CASIO Exilim F1) was placed perpendicular to the running lane at 15m from the start line. The height of the lens from the ground was 1.20m. The distance of the camera to the centre of the lane was 5m so that sufficient cycles of the sprint stride could be analysed. A field of view of 8m was sufficient to get a single ground contact for both legs of each drill for each athlete. The cameras recorded at 300fps with a shutter speed of 1/1000 to reduce blurring. To ensure enough light was available additional lighting (in form of the competition lighting used by the centre) was switched on for the duration of the session.

As the drills formed the warm-up for the subsequent training session athletes were not required to warm-up prior to the data collection. Each of the subjects performed the three drills in the running lane set up for analysis. Drills were performed from a standing start, and athletes were instructed to perform the drills as they would normally do in their warm-up and therefore all athletes wore flat training shoes. They performed each drill over a distance of 30m, and then turned around and performed the same drill in the opposite direction so that both left and right sides of the body were closest to the camera. Athletes received approximately 1-minute rest in between each drill.

As the focus of each of the drills was the swing phase of the gait cycle the analysis was limited to the phase between maximum hip flexion (MHF) and touchdown (TD). The MHF position was identified as an important position to attaining elite levels of maximal velocity in Chapter 4. Discussions with the coach regarding the perceived purpose of the drill and the findings in Chapter 4 directed the kinematic variables that were selected for comparison to maximal velocity sprinting. Firstly the general kinematics, followed by the lower limb joint angles at MHF and TD were derived, along with peak and average angular joint velocities between MHF and TD. Further in order to explore the intralimb coordination during drills and maximal sprinting joint angle-angle profiles between the hip, knee and ankle were developed. The angle data between MHF and TD were interpolated to 101 data points using a cubic spline technique.

The normality of the data set was assessed using the Shapiro-Wilk test in SPSS (Version 20). A non-significant result indicated the data was distributed normally and therefore a parametric test could be used to test for significant differences. Multiple paired t-tests were conducted using SPSS (Version 20.0) to identify differences between each drill and maximal velocity sprinting. The alpha level was set at $p<0.05$.

As the purpose of this study was to identify similarities between two variables a p value >0.05 indicates a lack of significant difference, and thus a degree of similarity. This method has been employed by a number of authors to investigate specificity in hurdle training (Cappa & Behm, 2011), ergometers in rowing (Fleming, Donne, Fletcher, & Mahony, 2012) and deep water running (Kilding, Scott, & Mullineaux, 2007).

6.3.3 Results & Discussion

Bulgarian split squat drop (BSq_{drop})

The BSq_{drop} lacks horizontal motion and therefore lacks specificity in horizontal speed principles. However as the exercise is performed by 'dropping' into it the BSq_{drop} has moderate specificity with respect to vertical speed, and is potentially comparable to the speed of the COM in the late flight phase of maximal sprinting. The phase from TD to MKF mimics the eccentric contraction at initial TD in sprinting. The time taken from TD to MKF was on average four times longer in the BSq_{drop} than sprinting, and therefore the BSq_{drop} lacks specificity in execution time. The time taken from TD to MKF can be compared to the eccentric time of a DJ reported by Coh and Mackala (2013). The authors reported an eccentric time of 0.070s for the elite sample and 0.077s for the sub-elite sample – suggesting minimising eccentric time is favourable. This reflects the findings of Chapter 4 as elite athletes minimised the knee flexion during stance by adopting a stiffer limb. The eccentric time is an indication of leg and musculotendinous unit stiffness which has been considered an important component of running economy (Arampatzis et al., 1999). An increase in stiffness reduces the distance the COM has to travel during stance, thus minimising the GCT and maximising the SF.

The joint angles and angular velocities will indicate whether the BSq_{drop} is specific with respect to the movement coordination principles. The lower limb joint angles at TD for both the BSq_{drop} and sprinting are presented in Figure 6-8. The trunk was significantly further forward at TD in the BSq_{drop} (12°) in comparison to sprinting (7°). This is attributed to the presence of a barbell on the shoulders which will likely induce more forward lean. At TD the hip angle was more flexed in the BSq_{drop} than sprinting, which was significantly different ($p<0.05$). The knee angle was also more flexed at TD in the BSq_{drop} in comparison to sprinting which was significantly different ($p<0.05$). Research provides strong evidence for joint angle training specificity, and both Knapik et al. (1983) and Kitai and Sale (1989) found the joint angle specificity extended to a range of 20° either side of the training angle. Thus it is proposed that despite the 18° and 24° difference of the hip and knee angles respectively at TD may still be within a range at which joint angle specificity may apply. In contrast the ankle angle at TD was much more dorsiflexed in the BSq_{drop} in comparison to sprinting and lacks specificity. The hip and knee angles at TD particularly affect the muscle lengths of the quadriceps, hamstrings and gastrocnemius – and therefore the extent to which they can accept the load of ground contact (force-length relationship). Subsequently it is proposed that when performing BSq_{drop} athletes should endeavor to adopt lower limb angles more specific to their individual maximal sprinting.

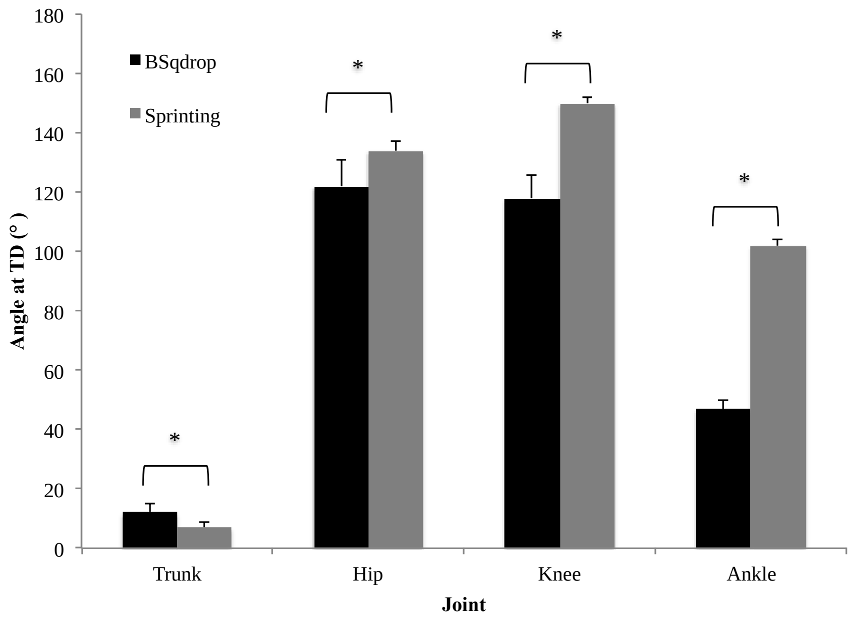


Figure 6-8 Joint angle comparison between BSq_{drop} and sprinting at TD. * indicates significant difference ($p<0.05$) between BSq_{drop} and sprinting

At MKF more flexion was observed at the hip, knee and ankle for the BSq_{drop} in comparison to sprinting, with all values identified as significantly different ($p<0.05$) (Figure 6-9). The ankle angle flexed minimally from TD to MKF (2.19°) indicating the load is predominantly mitigated through flexion of the hip and knee joints. The increase in flexion at MKF suggests a lack of stiffness of the lower limb and appears not to reflect the ground contact phase of sprinting.

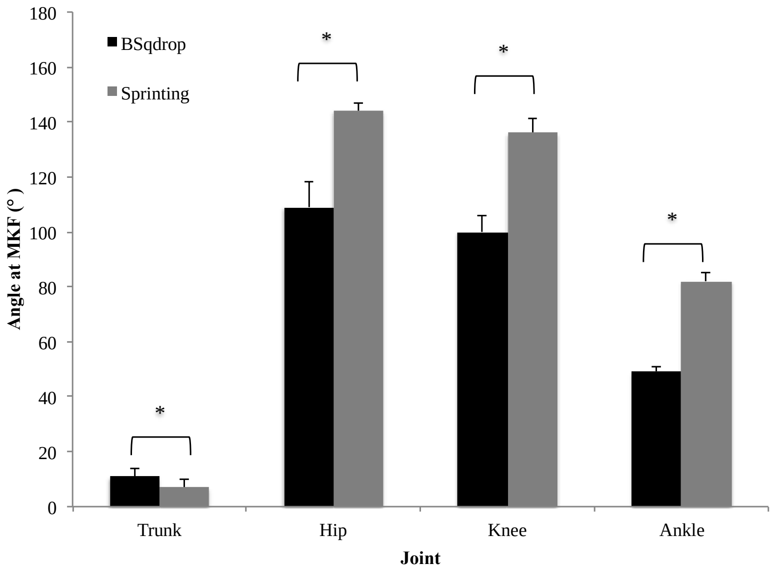


Figure 6-9 Joint angle comparison between BSq_{drop} and sprinting at MKF. * indicates significant difference ($p<0.05$) between BSq_{drop} and sprinting

Investigating the ROM of the joints from TD to MKF will allow comparisons to the early phase of stance at maximal velocity sprinting (Figure 6-10). The average ROM of the hip angle from TD to MKF was -13° in the BSq_{drop} and 10° in sprinting, which was significantly different ($p>0.05$). This indicates the hip is flexing from TD to MKF in the BSq_{drop}, whilst extending in maximal velocity sprinting. This would be expected as in sprinting the hip undergoes extension to transfer the COM from behind the body to in front of the body for TO. There was no significant difference ($p>0.05$) in the ROM of the knee joint between the BSq_{drop} (-10°) and maximal velocity sprinting (-14°). The findings in Chapter 4 found elite athletes minimised knee flexion during stance and that knee angle at MKF was strongly correlated to horizontal velocity (r=0.437). Thus reducing knee flexion is advantageous to attaining maximal horizontal velocity and by training this element in the BSq_{drop} this may transfer to maximal sprinting. As aforementioned the ankle undergoes very little change during the BSq_{drop} (2°) whilst in sprinting the ankle flexes by -20°, and therefore the ankle ROM was significantly different. This can be attributed to the fact that in maximal velocity sprinting the plantarflexor undergoes a stretch-shortening cycle in order to facilitate the ensuing concentric contraction, and subsequently a greater degree of flexion is advantageous to load the muscles. However in the BSq_{drop} the MKF is the final position (followed by a brief isometric contraction), and therefore the plantarflexion of the ankle does not need to be accentuated. Furthermore the type of shoe used in each exercise is likely to impact on the ankle angle. The BSq_{drop} was performed in a weightlifting shoe which has a slight heel lift, whilst sprinting was performed in running spikes and thus has much more flexibility.

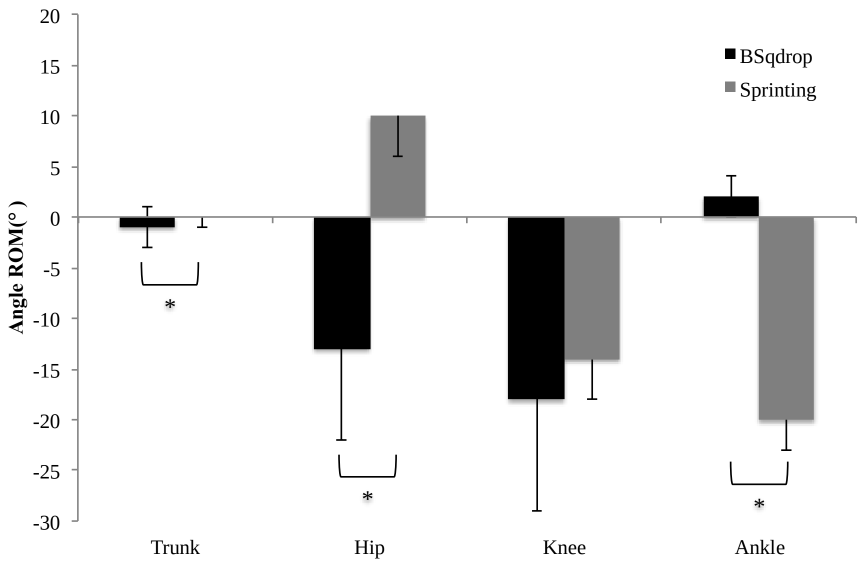


Figure 6-10 Joint angle ROM between BSq_{drop} and sprinting. * indicates significant difference ($p<0.05$) between BSq_{drop} and sprinting

Whilst the joint angles and ROM exhibit some degree of specificity in maximal velocity sprinting the deterministic model also indicates that joint angular velocity is critical to maximal velocity sprinting. The maximum and average angular velocities between TD and MKF were calculated for the hip, knee and ankle joints for the BSq_{drop} and sprinting (Figure 6-11).

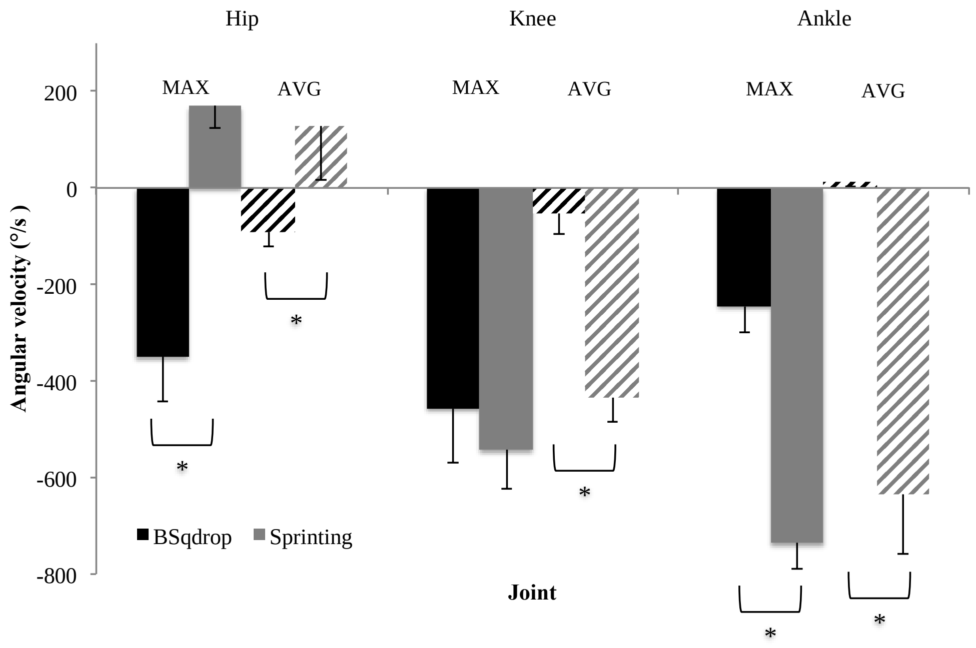


Figure 6-11 Maximum and average joint angular velocity comparison of BSq_{drop} and maximal velocity sprinting. * indicates significant difference ($p<0.05$) between BSq_{drop} and maximal velocity sprinting

The maximum hip velocity in the BSq_{drop} was -350°/s which was greater than the 169°/s in sprinting and was a flexion velocity as opposed to an extension velocity. The magnitudes of the average velocities were comparable but again in opposite directions. Research has not discussed the notion of whether training at specific velocities but in the opposing directions leads to strength gains as different muscle groups will be recruited for the flexion and extension phases. The mechanisms of velocity specificity outlined by Kawamori and Newton (2006) (Figure 2-13) indicate if a neural mechanism is responsible for the velocity specificity response this leads to an increased synchronisation of motor units, which then improves the overall coordination, therefore some adaptions may occur in the extension phase as in sprinting.

The maximum knee angular velocity in the BSq_{drop} was within 100°/s of that recorded in sprinting and was not significantly different ($p>0.05$) thus implying specificity. Coyle et al. (1981) proposed a neural mechanism was responsible for the velocity specificity effect as there was no change in muscle morphology. However if a neural mechanism is responsible it is then necessary to consider the phenomenon of 'intention' to move explosively (Behm & Sale, 1993). The athletes in the current study were instructed to move explosively, and thus potentially the velocity specificity may transfer to their maximal velocity sprinting. In contrast the average angular velocity was significantly lower in the BSq_{drop} in comparison to sprinting and lacks specificity. This was foreseen when the ROM from TD to MKF of the knee joint was specific between the BSq_{drop} and sprinting, but the time taken for this was 4 times longer in the BSq_{drop}, and subsequently must be a function of the angular velocity of this joint. The average angular velocity of the knee joint in the BSq_{drop} was -51°/s whereas in sprinting it was -375°/s. The low velocity in the BSq_{drop} is a result of the stabilisation phase towards the end of the lift where the knee angle fluctuation is minimal.

The average and maximum ankle angular velocities were significantly less in the BSq_{drop} in comparison to sprinting, yet this is attributed to the limited ROM of the ankle during the BSq_{drop} and the lack of subsequent concentric phase, and thus a high ankle angular velocity is not required in the BSq_{drop}.

Based on the conclusions of Chapters 4 and 5 a key criterion to maximise sprint velocity is to develop the highest possible GRF in the shortest possible time in order to minimise GCT. Development of force is a result of a connection between eccentric and concentric contractions. So whilst the BSq_{drop} lacks a concentric phase the specificity in loading principles can still be assessed with respect to the eccentric phase of sprinting. In contrast to sprinting the BSq_{drop} is not succeeded by a take-off phase and therefore the lift ends when the athlete has stabilised at the point of maximum knee flexion. To the authors knowledge no study to this date has investigated this type of squat and therefore comparisons with literature are limited. Comparisons of the initial impact phase could potentially be compared with those obtained for drop landing analysis, however drop landings tend to be performed with just body weight and performed from a greater height than the height dropped from in the single-leg squat. Fauth et al. (2010) investigated the kinetics of the forward lunge which represents a unilateral lower body exercise, however the lack of impact phase will limit comparisons with peak GRF and E-RFD.

It has been shown that adaptations to training are specific to the contraction type, whether it is isometric or isokinetic and subsequently whether it is an eccentric or concentric contraction. Subsequently the contraction type of the strength training exercise should exploit the same contraction types seen within the movement skill. The ground contact in maximal sprinting entails an eccentric contraction followed by a concentric contraction. In contrast the BSq_{drop} is an eccentric contraction followed by a brief isometric contraction as the athlete stabilises at the bottom position. Based on the loading principles outlined in Table 6-1 the BSq_{drop} has a high level of specificity in the loading principles as it entails a force acceptance phase of an eccentric muscle contraction following impact. In order to assess the degree of eccentric specificity between the BSq_{drop} and maximal sprinting the vertical GRF traces were compared (Figure 6-12), and key kinetic data was extracted (Table 6-7). Due to the lack of horizontal motion only the vertical forces were investigated.

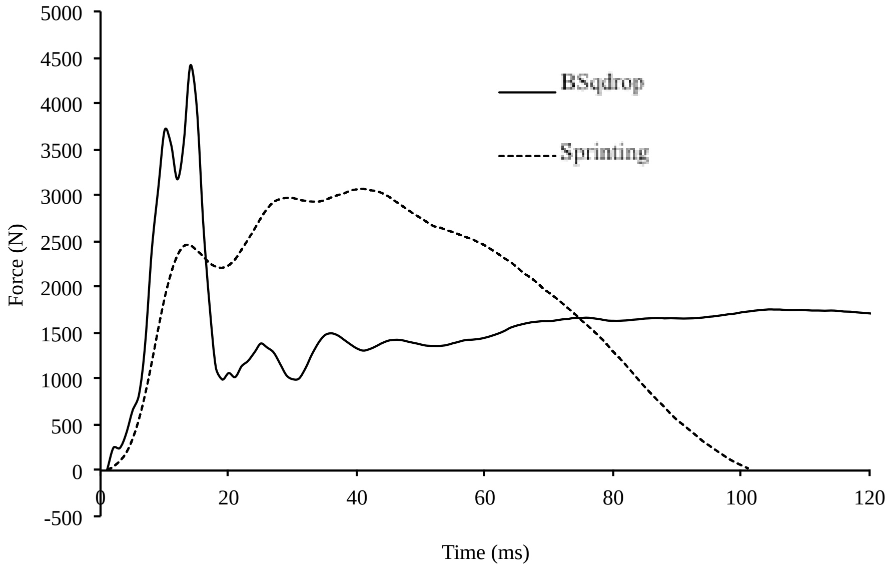


Figure 6-12 Vertical GRF of maximal sprinting and a BSq_{drop} for a representative athlete.

Table 6-7 Mean (±SD) kinetic variables of 6 subjects for sprinting and BSq_{drop}. Shading indicates there is a significant difference to sprinting ($p<0.05$).

	Time	Peak Fz		Time to peak Fz	Average force		Impulse	Force over 100ms		Peak E-RFD
	s	N	BW	s	N	BW	Ns	N	BW	N/s
BSqdrop	0.230 (0.090)	3416 (932)	3.92 (0.97)	0.006 (0.015)	1515 (453)	1.74 (0.23)	3489.4 (987.2)	1498 (306)	1.72 (0.32)	371 (163)
Sprinting	0.101 (0.008)	3162 (387)	3.68 (0.18)	0.033 (0.004)	1759 (219)	2.04 (0.13)	91.2 (17)	1779 (432)	2.05 (0.45)	184 (40)

The average force over the duration of the BSq_{drop} was specific to the average force in sprinting, both as an absolute value and when represented relative to BW. Visual inspection of the GRF trace (Figure 6-12) indicates similar force profiles as both traces exhibit a double peak. The timing of the first peak was similar between the BSq_{drop} and sprinting, however the time taken to reach the second (and maximum) peak was much later in sprinting (0.033s) in comparison to the BSq_{drop} (0.006s). The maximum Fz in a BSq_{drop} was 3416N (3.92BW) in comparison to the 3162N (3.68BW) in maximal sprinting. A paired t-test indicated no significant difference between the peak Fz of the BSq_{drop} and sprinting which indicates specificity in the magnitude of the load. This is a similar peak Fz reported by McNittgray (1993) when dropping from a height of 32cm (3.93BW), and close to the 3.52BW reported by Ali, Rouhi, and Robertson (2013) for a drop height of 20cm. Whilst performing the BSq_{drop} athletes had a barbell on their shoulders and subsequently the maximal vertical force is increased as the overall system load is larger. Based on the training principle of overload (Dick, 1980) the larger musculoskeletal work performed by the lower limb during the BSq_{drop} may produce specific muscular and neurological adaptations that facilitate an improvement in sprint performance. There was a large standard deviation (932N) in the peak Fz across the sample. This may be related to how aggressively the athletes approach the ground contact. McNittgray (1993) investigated the effect of impact velocity (manipulated by varying the drop height) on the peak Fz. Peak Fz ranged from 3.93W for an impact velocity of 2.5m/s and up to 10.96BW for an impact velocity of 5m/s. Thus it is clear the intention to move explosively will affect the peak GRF (Behm & Sale, 1993). Makaruk and Sacewicz (2011) propose that the E-RFD could be used to define the intensity of the drop jump as it includes both the GRF and time which is a key element due to the specificity of plyometric exercises. The E-RFD could be used in the current study to monitor the intensity adopted by each athlete to ensure they are consistent across repetitions and are maximising the specificity to sprinting. Rate of force development is depicted as the gradient as the slope on the force-time graph. The maximum rate of force development was greater in the BSq_{drop} (371kN/s) than sprinting (184kN/s), but was not significantly different and thus it can be concluded it is specific with respect to the rate of loading principle. The findings of Chapter 5 indicated the RFD was significantly different between a high and low vertical impulse trial implying its relevance to maximal velocity sprinting. However Young, McLean, and Ardagna (1995) found that maximum rate of force development was not strongly correlated to sprint performance and a more relevant measure is the force (relative to BW) applied over 100ms. This time period was selected as it represents a typical ground contact time in maximal sprinting, which coincides with the findings in Chapter 4. The average force applied over 100ms was 1498N (1.72BW) and 1779N (2.05BW) for the BSq_{drop} and sprinting respectively, which was not significantly different. This indicates a strong degree of specificity and confirms the relevance of this variable as proposed by Young et al. (1995). Furthermore it should be considered that the single-leg squat has the further advantage of training joints concurrently. Leirdal et al. (2008) found that training knee extensors and ankle plantarflexors concurrently as opposed to in isolation saw greater improvements in vertical jump performance. It provides strong justification of the loading specificity of the BSq_{drop} to maximal sprinting. It could be proposed to increase the specificity of the BSq_{drop} the ground contact phase is followed by a rebound concentric action to mimic the stretch-shortening cycle aspect of maximal velocity sprinting.

Deadlift

When discussing the specificity between the deadlift and maximal velocity sprinting it is directed by the movement principles outlined in the MSR framework (Table 6-1). The deadlift lacks specificity with regards to the speed principles as there is no horizontal motion and therefore no horizontal velocity. Whilst the primary direction of a deadlift is in a vertical direction the speed of this is low in comparison to sprinting due to the magnitude of the load lifted. As a result of this the execution times of a deadlift are much longer than the ground contact of sprinting. The total time for a repetition was 1.64s which is comparable to the typical 2s reported for a deadlift repetition (Garhammer, 1985), and alike to the 1.90s reported by McGuigan and Wilson (1996) in their research.

As the deadlift is a bilateral exercise it lacks specificity to the balance principles of maximal sprinting as it does not necessitate balance or proprioception for control. The coordination principles refer to the body position, and specifically the joint angular ranges of motions and angular velocities. The deadlift is a bilateral exercise whereas sprinting is a unilateral skill, therefore Taniguchi (1997) proposed crossover between the training methods would be limited due to a lack of specificity in the training mode. Yet both the deadlift and sprinting are performed in an upright position and therefore are specific with respect to posture. Kinematic comparisons between the two appear limited due to the notable differences in the positions adopted, however if the movement is broken down into the respective flexion and extension phases it can be investigated in more detail. The focus of the deadlift is the extension of the hip, knee and ankle joints as the barbell is lifted from the ground. This is achieved by contraction of the gluteus maximus accompanied by the quadriceps, adductor magnus and soleus muscle groups which have been shown to be important to maximum sprinting (Young et al., 2001a). Thus the deadlift can be compared to the extension phase of the ground contact of sprinting. Due to the lack of horizontal motion in a deadlift there is no MS time point, and therefore the extension phase will be defined from the point of MKF to the point of TO in sprinting, or the end of the lift in the deadlift.

The only comparable body position between the deadlift and sprinting is MKF at the start of the deadlift and MKF in sprinting (Figure 6-13).

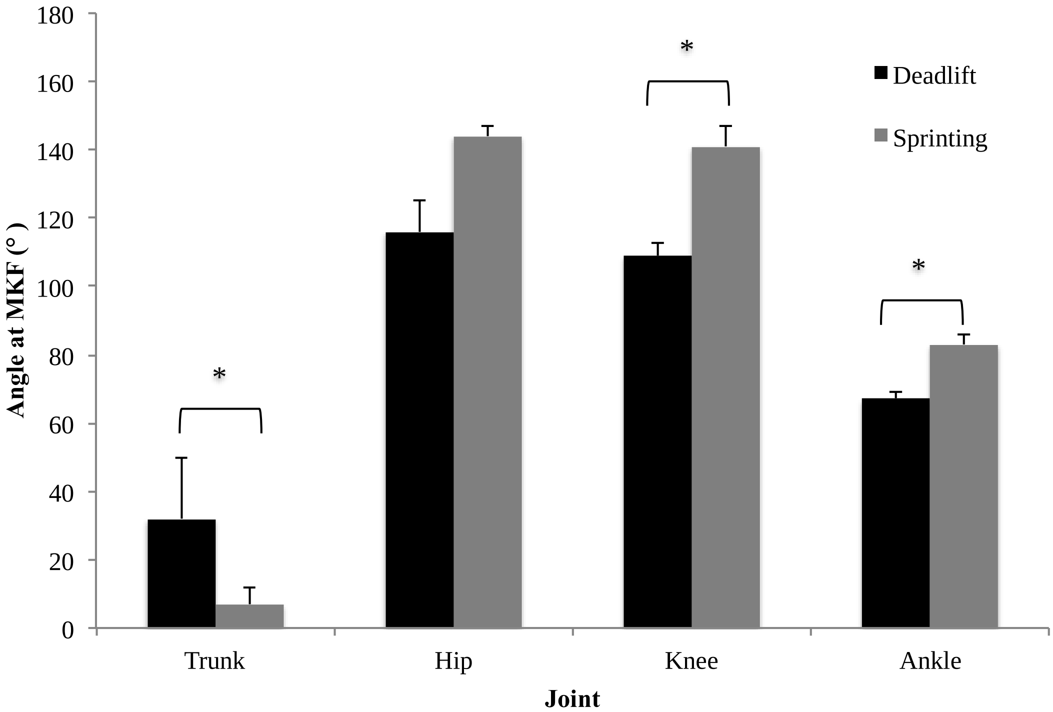


Figure 6-13 Comparison of joint angle at point of MKF between a deadlift and sprinting. * indicates significant difference (p<0.05) between the deadlift and sprinting

There is considerably more forward lean of the trunk in the deadlift (32°) compared to sprinting (7°) which was significantly different (p>0.05). This would be expected as in the deadlift the athlete must lean forward to grip the bar. The deadlifts in the current study were performed using a trap bar (based on instruction of the coach) meaning less trunk flexion is required to grip the bar. A more upright trunk in the deadlift is desirable as it keeps the back straight (Grabiner & Garhammer, 1989) and limits the requirement for the lower back musculature to produce the trunk extension (Horn, 1988), and thus may be the reasoning behind the coach selecting the trap bar for the lifts as opposed to a traditional barbell.

At the point of MKF in the deadlift and sprinting there was more hip flexion in the deadlift (116°) compared to sprinting (144°), however a paired t-test indicated this was not significantly different to sprinting (p>0.05). The hip angle is of particular importance as it determines the length of the hamstrings which primarily perform extension of the hip joint in a closed kinetic chain, and thus have a strong relevance to the ground contact phase of sprinting. The knee angle at MKF in sprinting is 141° which is significantly more than in the deadlift (109°). However the degree of knee flexion at MKF in the deadlift (i.e. the start of the deadlift) is limited by the height of the trap bar. Subsequently the knee angle varies amongst subjects likely due to differences in height, arm and leg length. The ankle angles between the deadlift and sprinting were significantly different ($p<0.05$), yet this is because the deadlift is performed with the foot flat on the ground, whilst in sprinting the foot is in a plantarflexed position with a forefoot contact. Furthermore the type of shoe used in each exercise is likely to impact on the ankle angle. The deadlift was performed in a weightlifting shoe which has a slight heel lift, whilst sprinting was performed in running spikes and thus has much more flexibility.

In order to establish whether the deadlift is specific with respect to the force-velocity component of the movement coordination principles the maximum and average angular velocities for the hip, knee and ankle joints for the deadlift and maximal sprinting are presented in Figure 6-14.

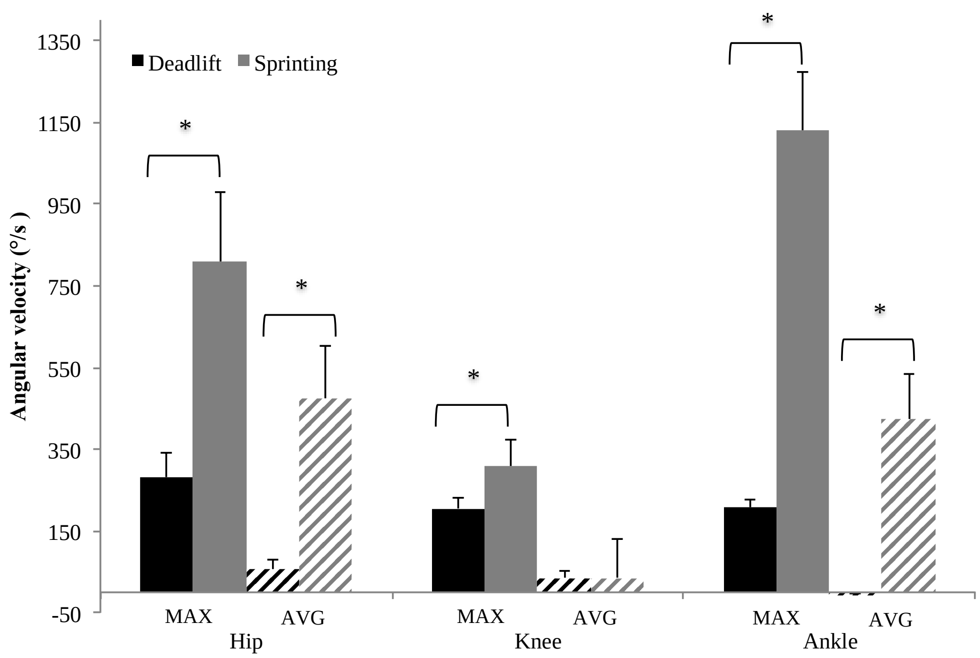


Figure 6-14 Comparison of maximum and average joint angular velocities during a deadlift and sprinting (from MKF to TO/end). * indicates significant difference ($p<0.05$) between deadlift and sprinting

The maximum hip velocity achieved in the deadlift was 281°/s which is slower than the 808°/s reported for the extension phase of sprinting. However 281°/s is still a comparatively high angular velocity as described by the literature, and it is likely this maximum velocity occurred towards the end of the deadlift when the athlete had gained momentum with the barbell. As expected the average angular velocity of the hip was much lower in the deadlift (55°/s) compared to sprinting (474°/s) which was significantly different ($p<0.05$). However this is due to the initial phase of the deadlift where the athlete must overcome the inertia of the bar to raise it off the ground. An angular velocity is 55°/s is reflective as a 'slow' velocity as defined by the literature, whilst sprinting is would be defined as a 'high' angular velocity. The nature of velocity specificity is that strength gains tends to be restricted to the velocities at which the muscles are trained (Morrissey et al., 1995). Following a 6-week knee extension isokinetic training programme at velocities of 60°/s subjects only saw improvements at that velocity with no transfer to higher velocities (300°/s). This reflects the average velocity of the deadlift and thus it is hypothesised strength gains may not be seen at the higher velocities in maximal velocity sprinting.

The maximum knee velocity recorded in the deadlift was 205°/s which was significantly less ($p<0.05$) than the 308°/s in sprinting, and thus lacked specificity. Yet this is still reflective of an 'intermediate' velocity as defined by Kanehisa and Miyashita (1983) who found subjects who trained at intermediate angular velocities saw improvements across all velocities. The average knee velocity was identical (36°/s) between the deadlift and sprinting and was not significantly different ($p>0.05$), indicating specificity. The comparable low velocities between both the deadlift and sprinting can be attributed to the lack of knee flexion in the stance phase of sprinting (Chapter 4), and thus a high extension velocity is not required. As discussed above training at low velocities leads to strength improvements at those velocities (Coyle et al., 1981), and thus it is hypothesised the strength gains around the knee joint may transfer to the extension phase of maximal velocity sprinting, and therefore displays specificity with respect to the force-velocity component of the MSR.

In the deadlift the average ankle velocity is a negative value which represents a flexion velocity, whilst in sprinting the average velocity is positive and represents an extension velocity, and therefore these values were significantly different ($p<0.05$).

This would be expected as in the extension phase of sprinting the ankle must plantarflex to enable the athlete to push off the ground, were as the deadlift is performed with the foot flat on the ground and therefore this degree of extension is not required.

Swinton, Stewart, Agouris, Keogh, and Lloyd (2011) compared the kinematics and kinetics of the deadlift using both straight and hexagonal barbells across a range of submaximal loads. The authors found subjects were able to lift a heavier load using a hexagonal barbell, and that the design of the hexagonal barbell resulted in lower joint moments at the lumbar spine hip and ankle, but an increased peak moment at the knee. Further to this greater peak force and velocities were produced using the hexagonal barbell and thus its use should be considered by sprint athletes who are aiming to maximise the specificity to sprinting.

Graham-Smith et al. (2010) stressed the importance of not confining the concept of specificity to replicating the movement patterns, but that the loading specificity of strength training exercises should also be considered. The loading principles refer to the type of loading, magnitude of loading and rate of loading and how they replicate those of maximal velocity sprinting. Sprinting entails an eccentric contraction at ground contact followed by a concentric contraction from mid-stance through to toe-off. The deadlift is a concentric contraction as the weight is lifted from the ground, and then is typically dropped at the completion of the lift so there is no eccentric element of lowering the weight to the ground. To compare the magnitude and rate of loading between the deadlift and maximal velocity sprinting the key kinetic variables identified in Chapter 5 are presented in Table 6-8. The peak Fz in the deadlift was 3500N, which is much greater than the maximum GRF reported for the deadlift by Fauth et al. (2010) (1520N). This may be attributed to the differences in relative intensity between the 2 studies, the current research used a 3RM load whereas Fauth et al. (2010) used a 6RM load. Yet for athlete's B and D the load lifted was below 80% 1RM and therefore is no longer working on maximum strength, and therefore a comparison to the loading characterstics of trials >80% 1RM is limited. Whilst this was out of control of the researcher it should be considered when observing the findings.

Comparisons to maximal sprinting are problematic as the deadlift is bilateral exercise and therefore the force is developed through both feet. Dividing the total force by two would be inaccurate as in sprinting the entire bodymass is supported by one limb, whilst in the deadlift it can be presumed the body mass is divided evenly between the two limbs. The peak force of 3500N is slightly higher than the 3162N recorded in sprinting. The force applied over 100ms is a variable calculated to facilitate comparisons with the typical ground contact time for sprinting. The force over 100ms in a deadlift was 1512N which was less than 1779N in sprinting. As would be expected the peak RFD is over 10 times higher in sprinting due to the impact at TD which is not present in the deadlift.

Comfort, Allen, and Graham-Smith (2011) identified that weightlifting exercises with a greater RFD likely result in greater power outputs and therefore more suitable to developing power, whereas a lift such as the deadlift may be more appropriate at developing strength in a periodised programme (as used by elite sprinters). General or non-specific training is required to provide a base from which to work from, and the level of specificity of training should generally increase as the competitive peak approaches. The analysis in the current thesis was done in the winter season and thus may reflect a general phase of training. The use of the deadlift in the latter stages of a training season should be limited and exercises adopted should display higher specificity to maximal velocity sprinting.

	Time	Average force		Impulse	Peak Fz		Time to peak Fz	Force over 100ms		Peak RFD
	s	N	BW	Ns	N	BW	s	N	BW	N/s
Deadlift	1.310 (0.21)	2907 (483)	3.34 (0.32)	3808.1 (421)	3500 (581)	4.02 (0.35)	1.150 (0.270)	3024 (458)	3.34 (0.28)	11014 (3579)
Sprinting	0.101 (0.008)	1759 (219)	2.04 (0.13)	91.2 (17)	3162 (387)	3.68 (0.18)	0.033 (0.004)	1779 (432)	2.05 (0.45)	183575 (40180)

Table 6-8 Mean kinetic variables of 6 subjects for sprinting and deadlift

The specificity of running drills to maximal velocity sprinting will be discussed based on the speed, movement coordination and balance principles outlined in Table 6-1. The mean and standard deviations of the general kinematics for each of the drills and maximum velocity sprinting are presented in Table 6-9.

Table 6-9 Mean (±SD) of the general kinematics for sprinting and drills. Shading indicates the variable is significantly different between the drills and sprinting ($p<0.05$).

		Sprinting	A Skip	B Skip	Scissor
Horizontal velocity (m/s)	Average	**10.31 (0.53)**	2.31 (0.40)	2.70 (0.33)	5.19 (0.83)
Time MHF - TD (s)	Change	**0.130 (0.010)**	0.280 (0.020)	0.310 (0.061)	0.161 (0.029)
COM height (m)	MHF	**1.01 (0.04)**	1.12 (0.09)	1.13 (0.07)	1.01 (0.08)
	TD	**0.97 (0.04)**	1.03 (0.03)	1.05 (0.04)	0.96 (0.07)
	Change	**-0.04 (0.02)**	-0.09 (0.07)	-0.08 (0.06)	-0.05 (0.03)
Vertical velocity (m/s)	Average	**0.09 (0.29)**	-0.15 (0.25)	-0.46 (0.30)	-0.34 (0.15)
	MHF	**0.60 (0.17)**	-0.13 (0.25)	-0.39 (0.31)	0.59 (0.23)
	TD	**-0.67 (0.17)**	-1.13 (0.25)	-1.34 (0.39)	-0.97 (0.21)
	Change	**-1.26 (0.29)**	-1.00 (0.33)	-0.95 (0.49)	-1.56 (0.29)
D_{TD} (m)	TD	**0.30 (0.05)**	0.30 (0.04)-	0.34 (0.05)-	0.28 (0.07)-

All drills were performed significantly slower than sprinting ($p>0.05$). The A skip and B skip were performed at average horizontal speeds of 2.31 and 2.70 m/s respectively, which represents a speed of only 22 and 25% of the velocity reached during maximal sprinting. The scissor drill was performed at a greater velocity of 5.19 m/s which is closer to 50% of maximal sprinting velocity. Lauder and Payton (1995) stated that training drills should be performed at the same speed as the target skill. However if the drill is to be utilised to learn the movement patterns of the skill in the coordination phase of learning it may be less important for drills to performed at the same speed as the final skill (Wilson et al., 2009). The vertical velocity was measured to establish whether the drills were similar with respect to vertical speed. The average vertical velocity in sprinting was positive (0.09m/s) whilst in all drills the average vertical velocity was a negative value. This indicates the drills were executed with more vertical motion, which would be expected as the drills were instructed to be performed with a ‘skipping’ motion. The vertical velocity at specific time points is likely to show more similarity. The findings in Chapter 4 and 5 dictated the MHF and TD positions as important in maximal velocity sprinting due to their effect on the vertical impulse and peak braking force respectively. There was no significant difference (and thus specificity) in vertical velocity at MHF between the scissor drill (0.59m/s) and sprinting (0.60m/s). However at the point of TD the vertical velocity in the scissor drill was greater than sprinting and no longer specific. So whilst the *change* in vertical velocity in the B skip and scissor drill was comparable to sprinting, the lack of similarity at key events (TD and MHF) indicates a lack of specificity to sprinting. The vertical oscillation of the COM gives an indication of the flight mechanics to compare to sprinting as the drills do not have a full flight phase. There was no significant difference for change in COM height between the scissor drill and sprinting ($p>0.05$), which indicates an element of specificity. The A and B skip displayed more vertical oscillation than maximal sprinting. Thus this element lacks specificity as more vertical motion would allow more time to reposition the limbs in flight, and therefore the vertical impulse requirements would be different to sprinting. Chapter 5 introduced the concept that the magnitude of vertical impulse may be related to the time required to reposition the limbs in the swing phase. The time from MHF to TD is the time available to extend the hip and knee prior to ground contact and was the coaching focus of all three drills investigated (Harrison & Warden, 2003). This phase was significantly longer in all drills in comparison to sprinting, and was over twice as long for both the A and B skip. Subsequently there was more time available to prepare the limb for the optimum position at TD. Both the deterministic model and technical model developed in Chapter 4 identify the D_{TD} of the foot relative to the COM as influential to maximal velocity. The mean D_{TD} in sprinting was 0.30m, which was similar to the A skip (0.30m), B skip (0.34m) and scissor drill (0.28m). The D_{TD} for each of the drills was not significantly different to sprinting ($p>0.05$) and therefore is specific. The D_{TD} is determined by the lower limb joint angles and therefore it warrants a more detailed investigation of these elements and the movement coordination principles for the drill as a whole. The joint angles at key positions for each of the drills and sprinting are presented in Table 6-10.

Table 6-10 Mean (±SD) joint angles for sprinting and drills at key events (MHF and TD). Shading indicates the variable is significantly different between the drill and sprinting (p<0.05).

Joint	Time point	**Sprinting**	A Skip	B Skip	Scissor
Trunk (°)	MHF	**9 (4)**	7 (2)	6 (4)	9 (3)
	TD	**12 (4)**	5 (3)	4 (2)	6 (2)
Hip (°)	MHF	**103 (6)**	69 (8)	58 (6)	114 (12)
	TD	**147 (3)**	156 (8)	151 (5)	151 (5)
	Change	**44 (6)**	87 (7)	93 (6)	37 (10)
Knee (°)	MHF	**64 (9)**	50 (7)	70 (15)	140 (16)
	TD	**150 (5)**	155 (9)	151 (5)	150 (4)
	Change	**86 (10)**	107 (9)	81 (18)	10 (17)
Ankle (°)	MHF	**99 (7)**	76 (7)	76 (8)	80 (5)
	TD	**103 (5)**	94 (11)	92 (9)	85 (8)
Thigh (°)	TD	**23 (11)**	39 (6)	42 (4)	16 (9)

The trunk angle at the point of MHF was not significantly different (p>0.05) between sprinting and each of the drills, indicating a good level of specificity. Specificity in the trunk angle is important as Kivi (1997) stressed the importance of maintaining the same upper body position when performing the drills in order to maximise the transference to sprinting. The trunk angle at TD was significantly smaller (p<0.05) (i.e. less forward lean) in each of the drills in comparison to sprinting. The trunk angle has an impact on the position of the COM and therefore it is proposed that athletes should aim for more forward lean in the drills to imitate the trunk position of sprinting.

Maximum hip flexion was identified as an inherent factor to maximal velocity sprinting in Chapter 4, with better athletes displaying a greater angle of maximum hip flexion in the swing phase. A greater MHF angle increases the range of motion over which the leg can be accelerated towards this ground. This enables the athlete to a) get the leg underneath the body to and b) increases the likelihood of a negative foot speed at TD which minimises the peak braking force (Figure 5-5). The degree of MHF (measured relative to the vertical) varied dependent on the type of the drill, and all were significantly different to sprinting (p<0.05). Both the A and B skip had a greater degree of hip flexion compared to sprinting, whilst the scissor drill had a smaller degree of hip flexion compared to sprinting. This could be viewed subjectively by a coach as the thigh above parallel in the A and B skip (<90°) and the thigh below parallel in the scissor skip (>90°). The MHF in the A and B skip was over exaggerated (69° and 58° respectively) in comparison to maximal sprinting. As a high knee position is indicative of an elite performance an over exaggeration of this position in drills may actually be advantageous in instilling the technique into maximal sprinting. The scissor drill (114°) was closest to sprinting (103°), but was still significantly different. Brady and Maraj (1999) conducted a limited analysis of the 'straight-leg bound' (i.e. scissor drill) with a sample of four elite male sprinters with an average 100m PB time of 10.28s which is comparable to the sample used in this thesis. However the authors only reported minimum and maximum hip angles and the MHF angle was 134° which is less than the 114° in the current study. The knee angle at the point of MHF will determine the range of motion over which the knee must extend approaching ground contact. The knee angle at MHF in the A skip (50°) was significantly smaller than sprinting, however in the B skip it was 70° which was not significantly different to sprinting (64°). Unsurprisingly there was a significant difference between sprinting and the scissor drill as this is performed with a relatively straight leg and the athlete is instructed to keep the same degree of knee flexion throughout.

Chapter 5 concluded hip angle at TD had a strong correlation (r=0.565) to maximal velocity sprinting and was correlated to the magnitude of the braking force and therefore critical to maximal velocity sprinting. The hip angle at TD for all drills were within 10° of that observed in maximal sprinting (147°), however the A skip was identified as significantly different ($p<0.05$). The similarity in hip angle at TD between the drills and sprinting indicates an element of specificity and potential transfer to sprint technique. The knee angle at TD in sprinting also had a strong correlation to maximal velocity (r=0.579). The knee angles at TD for the A skip (155°), B skip (151°) and scissor (150°) were all within 5° of the knee angle in sprinting (150°) and were not significantly different which indicates a very high degree of specificity. The 5° and 10° differences between the drills and sprinting for the knee and hip joints respectively falls within the 20° range proposed by Knapik et al. (1983) for strength gain benefits. Whilst the focus of running drills is not strength development the similarity in joint angles at key positions of the stride may develop the neural adaptations as Thepaut-Mathieu et al. (1988) has shown there is greater motor unit activation at the joint angles trained.

There was an overall trend for the ankle to be more dorsiflexed during drills in comparison to sprinting. Ankle dorsiflexion is a common coaching cue used by elite sprint coaches, and subsequently it is possible this is exaggerated in the drills as the athlete has been instructed to focus on this element. Dorsiflexion of the ankle during late swing is necessary to develop pretension prior to the ground contact phase (Bosch & Klomp, 2005).

As aforementioned the focus of the drills is the rapid extension of the limbs aiming to replicate the latter stage of swing in maximal sprinting. A study of the joint angular velocities will determine whether this is being achieved, and whether drills are specific with respect to the force-velocity movement coordination principle. The technical model in Chapter 4 identified the peak and average angular velocities as critical to sprinting and therefore these variables were measured between the point of MHF and TD for each of the three lower limb joints. The peak and average angular velocities of each joint are reported in Table 6-11.

Table 6-11 Mean (±SD) peak and average joint angular velocities from sprinting and drills. Shading indicates the variable is significantly different ($p<0.05$) to sprinting.

Joint		**Sprinting**	A Skip	B Skip	Scissor
Hip (°/s)	Peak	**530 (73)**	499 (72)	490 (51)	360 (79)
	Average	**332 (54)**	306 (36)	297 (22)	226 (43)
Knee (°/s)	Peak	**1218 (148)**	668 (104)	697 (97)	261 (115)
	Average	**656 (76)**	374 (43)	259 (59)	56 (102)
Ankle (°/s)	Peak	**277 (109)**	331 (91)	266 (98)	205 (163)
	Average	**21 (45)**	62 (42)	54 (35)	33 (40)
Foot speed (m/s)	TD	**3.07 (0.55)**	1.70 (0.35)	2.64 (9.57)	2.33 (0.45)

The average hip extension velocity between MHF and TD in sprinting was 332°/s, with an peak velocity of 530°/s. Interestingly this peak value is less than reported by

Kivi (1997) (652°/s) despite the less elite sample. Chapter 5 found maximum hip extension velocity was strongly correlated ($r=0.595$) to maximal velocity and therefore higher velocities would be expected in this study due to the greater sprint velocities. The peak and average hip extension velocities in the A and B skip were slightly lower than sprinting but were not significantly different. Whilst the scissor drill was specific with respect to joint angles it lacks specificity with regards to hip extension velocity as the average hip extension velocity (226°/s) was almost a 1/3 less than in sprinting and was significantly different ($p<0.05$). As the focus of the A and B skip is the rapid extension of the leg towards the ground it can be concluded the drills are achieving this element, and consequently are specific to sprinting. Velocity specificity is important as the speed of the movement has an important function on the levels of loading, the ability to generate force and the typical movement or ground contact times (Graham-Smith et al., 2010). The angular velocities experienced in the drills are all equivalent to the 'fast' velocities investigated in velocity specificity research, which confirms the hypothesis proposed by Kanehisa and Miyashita (1983) that athletics performances occur at limb speeds greater than 180°/s. The intent to move explosively is integral to the neural mechanisms associated with adaptations in high-velocity strength and rate of force development (Ives & Shelley, 2003). In the drills the athletes are focusing on the active acceleration of the limb towards to the ground and therefore this conscious intent to move explosively may enhance transfer to maximal velocity sprinting.

The peak and average knee angular velocities in the drills were significantly less than sprinting and thus displayed a lack of specificity. The peak angular velocity of the knee in sprinting (1218 °/s) was almost twice that of the A skip (668°/s) and B skip (697°/s), and 4.5 times greater than the scissor drill (261°/s). Similarly the average angular velocity of the knee joint in sprinting (656°/s) was greater than compared to A skip (374°/s) and B skip (259°/s). The average angular velocity in the scissor drill was very low (56°/s), however this would be expected as the knee remains approximately in the same position throughout the drill and therefore there is very little knee flexion/extension.

The peak and average ankle angular velocities both demonstrated a high correlation to maximal velocity sprinting (see Chapter 4) which stresses the importance of the specificity of these elements. Interestingly although there was a lack of specificity in ankle angles at key events between the drills and sprinting, the peak and average ankle angular velocities were statistically similar between all drills and sprinting. Whilst the hip and knee angular velocities were greater in sprinting in comparison to the drills, the ankle angular velocities were higher in the drills than sprinting. This suggests there is much more movement of the ankle joint during drills compared to the sprinting. As previously mentioned this may be related to the fact the ankle angle is a key coaching cue in drills and therefore may fluctuate more than during sprinting.

Chapter 4 reported foot speed at touchdown showed a moderate correlation (0.352) to maximum velocity. Furthermore in Chapter 5 it was proposed a greater foot speed relative to the COM led to a reduction in the peak braking force at TD. To enable comparisons between sprinting and drills the foot speed was calculated as the absolute value at TD (m/s) as opposed to relative to the COM as in Chapters 4 and 5. This allowed for comparisons between the drills and sprinting despite the large differences in the horizontal velocity at which the drills are performed. Foot speed at touchdown was significantly lower in all drills in comparison to sprinting. The B skip had the most comparable value (2.64m/s) to maximal velocity sprinting (3.07m/s). The significant difference can be attributed to the very large standard deviation of foot speed in the B skip (±9.57m/s) which is related to a variation in an execution of the drill within the sample. This is potentially linked to the intention to move explosively as discussed earlier. It is proposed this should be a further coaching focus of the drills to encourage athletes to reach foot speeds similar to those experienced in maximal velocity sprinting in order to maximise specificity.

If the primary purpose of a drill, as suggested by coaches, is to replicate the movement patterns used in sprinting then the use of coordination strategies may provide a better indication of their effectiveness as a drill as opposed to single joint kinematics (Wilson et al., 2009). An angle-angle plot will provide insight into the sequencing of movements and the presence of cyclical movements to correspond with the movement principles of the MSR (Table 6-1). The joint angle profiles between MHF and TD were interpolated to 101 data points to allow for comparisons between the drills and sprinting. Two joint couplings will be considered for the purpose of this research: hip flexion/extension-knee flexion/extension (HK) and knee flexion/extension-ankle dorsi/plantarflexion (KA) to coincide with the joint couplings used to assess maximal velocity sprint running in Chapter 4.

The joint coupling diagram of the A skip (Figure 6-15) better indicates the similarities and differences in coordination strategies between the drill and sprinting. The HK coupling in the A skip begins further to the left hand side of the graph and lower down in comparison to sprinting, indicating that at MHF both the hip and knee are more flexed in the A skip. Yet at TD the HK coupling is in a similar lateral position on the graph indicating specificity in the knee angle, however the coupling finishes higher on the plot thus indicating a greater degree of hip extension in the A skip. Both the width and height of this coupling on the plot are larger than in sprinting indicating a greater ROM in the drill. The gradient of the coupling line indicates the rate of flexion/extension of one joint in the coupling in relation to the other. A linear line at 45° would indicate both joints in the coupling were flexing/extending at the same rate. This can be observed in the HK coupling of the A skip, however approaching TD the gradient of the line increases, indicating the hip extends at a greater rate than the knee. The HK coupling in sprinting has a much flatter gradient throughout the movement, indicating the knee extends quicker in comparison to the hip. Thus the A skip lacks specificity with regards to the sequencing as movements as highlighted in the movement coordination principles element of the MSR. The KA coupling is a horizontal line in both the A skip and sprinting which shows the knee is extending at a greater rate in comparison to the ankle. The rate of knee and ankle extension is specific between the A skip and sprinting as the coupling lines runs parallel, indicating specificity in coordination strategies and sequencing of movements from proximal to distal. The KA coupling in the A skip lies lower on the graph thus demonstrating the ankle is more plantarflexed in the drill which as discussed earlier was attributed to a coaching cue provided from coaches. As with the HK coupling the KA coupling has a greater ROM due to the greater degree of knee flexion at MHF (begins further to the left). The KA coupling in sprinting predominantly undergoes a period of extension from MHF-TD (indicated by moving from left to right on the graph), however then switches to flexion just preceding TD (line changes direction). This coincides with the findings of Chapter 5 that demonstrated the knee has a flexion velocity at TD to reduce the D_{TD} and minimise the braking forces. In contrast neither the HK or KA coupling in the A skip show this phase of flexion and therefore lack specificity to sprinting. The angle-angle plot gives a visual representation of the coordinative patterns used in the drills in comparison to sprinting. Despite the apparent similarity in pattern the difference in magnitudes of the HK and KA couplings have a large effect on the interjoint coordination.

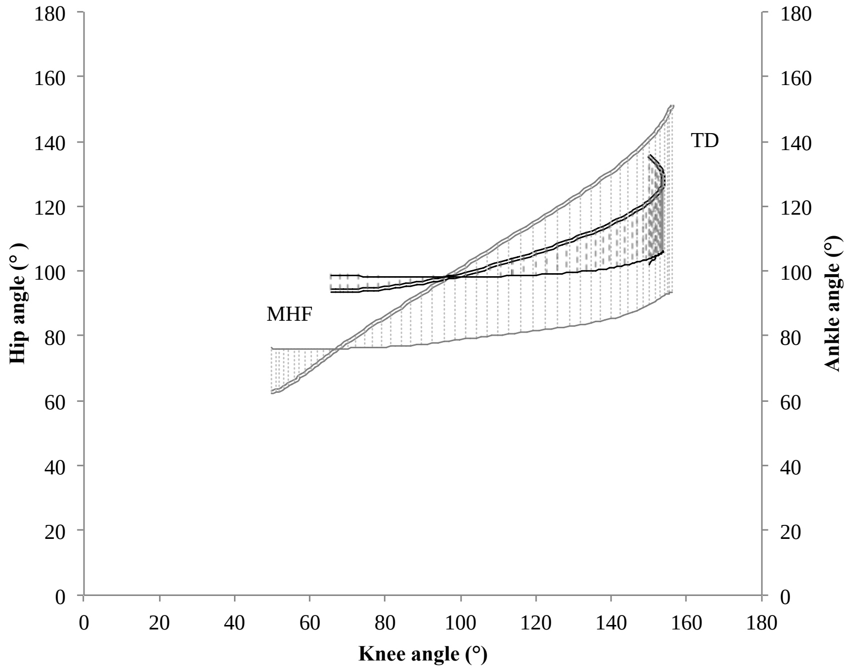


Figure 6-15 HK coupling (double line) and KA coupling (single line) of sprinting (black) and the A skip drill (grey)

The angle-angle plot of the B skip represents more specificity in the coordination strategies in comparison to the A skip. The similarity in the location of the plots with respect to their left-right position and the width of the two plots indicates specificity both in the knee angle at MHF and TD and the ROM of the knee angle. However as both the HK and KA coupling lie lower on the graph in comparison to sprinting this indicates a greater degree of hip flexion and ankle dorsiflexion throughout the drill. Whilst the magnitude of the hip and ankle angles differs the angle-angle plot demonstrates a degree of specificity in the coordination strategies employed. The HK coupling in the B skip is approximately parallel to that coupling in sprinting, with a period of extension followed by a brief period of knee flexion (change in direction) approaching TD. The gradient of the lines are similar thus indicating specificity in the rate of hip and knee extension/flexion in relation to each other. As aforementioned the difference in position on the graph is a function of the hip angle which is more flexed at MHF in the A skip. However by TD the hip angle is similar which is demonstrated by a similarity in the height on the graph (and lack of significant difference in a paired t-test). As with the A skip the KA coupling runs parallel to sprinting, and only differs in magnitude as a function of the ankle angle. Yet the graph illustrates a lack of specificity in the KA coupling approaching TD. In sprinting the KA coupling switches to right to left and goes down which is indicative of knee flexion and ankle flexion. However in sprinting whilst the switch from right to left is evident the line then travels upwards indicating the knee flexion is accompanied by ankle extension. Whilst the A skip occupies the same position on the plot as sprinting it is concluded that the B skip is more specific to sprinting due to the similarities in coordination strategies.

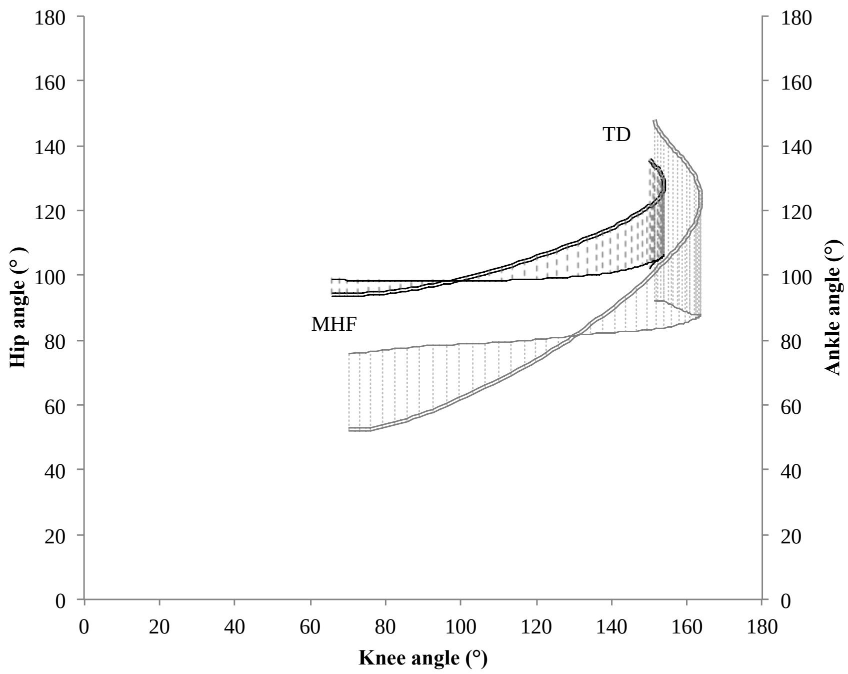


Figure 6-16 HK coupling (double line) and KA coupling (single line) of sprinting (black) and the B skip drill (grey)

The scissor drill demonstrates differing coordination strategies to both the A and B skip. The narrowness of the plot for the scissor couplings is representative of the minimal knee extension in the drill, which would be expected as this has also been described as the ‘straight-leg bound’. As with both the A and B skip the KA coupling is lower on the graph due to a greater degree of ankle dorsiflexion in the drill. Similarly with the B skip the KA coupling lacks specificity in the coordination strategy to sprinting approaching TD with ankle plantarflexion as opposed to ankle dorsiflexion. The HK coupling lies on the same vertical position on the plot and occupies the same lateral position on the plot for the latter stages of sprinting, indicating specificity in both the hip and knee angles. The coupling indicates a curvilinear pattern which is indicative of a period of extension followed by a period of flexion in the knee angle. The pattern is similar to the coupling to sprinting, however in the scissor drill there is a greater degree of hip extension at MHF (starts higher on graph) and a greater degree of hip extension at TD (ends higher on graph). If the ankle angle were to be more plantarflexed the drill the scissor drill would demonstrate a very high level of specificity to sprinting in the latter stages of the MHF-TD phase.

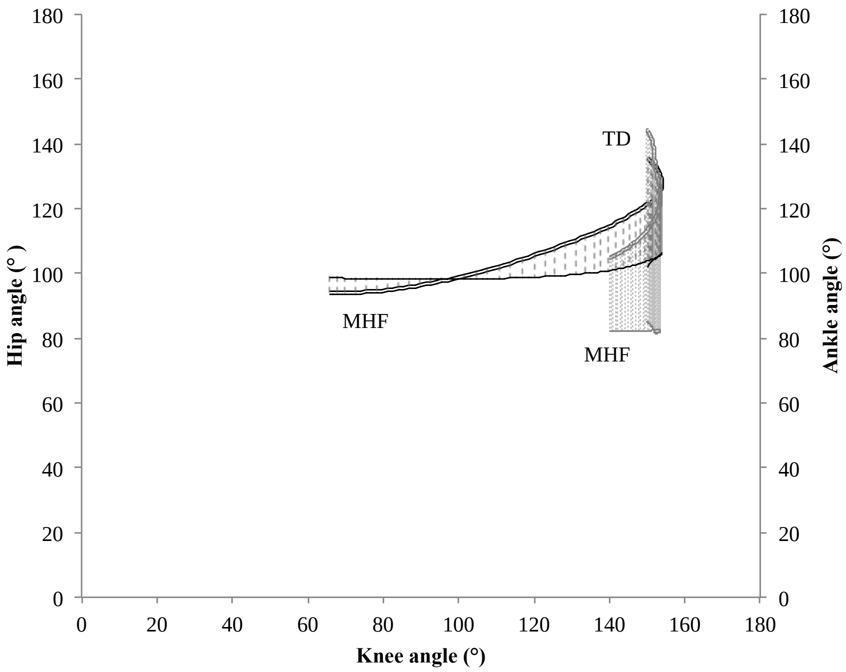


Figure 6-17 HK coupling (double line) and KA coupling (single line) of sprinting (black) and the scissor drill (grey)

The results presented in this chapter reveal that each of the running drills investigated are specific to different elements of maximal velocity sprinting. The A skip lacks specificity with respect to the joint angles at MHF and TD, but when the overall coordination strategy is considered the coordination patterns are similar. Furthermore the hip and ankle angular velocities in the A skip are specific to sprinting. It is proposed the B skip is more specific to sprinting as it also displays strong similarities in the hip and knee kinematics of sprinting, which was illustrated as similar coordination patterns on an angle-angle plot. The scissor drill only displayed similarity in the vertical motion of the COM along with the joint angles at key positions. However the scissor drill lacked specificity in the joint angular velocities. All three drills investigated are cyclical in nature, conducted in postures similar to sprinting and are unilateral exercises, and thus display a strong degree of movement coordination specificity to sprinting.

6.4 Conclusion

The ranking of a Bulgarian split squat changed following the MSF, and there was variance in the MSR value between coaches. Therefore this exercise was investigated further with a group of elite athletes in order to quantify the specificity to maximal velocity sprinting. The deadlift was the lowest ranked exercise, and its specificity to maximal velocity sprinting could be questioned. Therefore this was also investigated further to identify any kinematic or kinetic characteristics that are comparable to maximal velocity sprinting.

The BSq_{drop} was specific to sprinting in terms of both the coordination and loading principles. The BSq_{drop} is a unilateral exercise and is performed in a upright position and therefore reflects the posture of maximal sprinting. However the joint angles at TD were not specific and it is proposed athletes should aim to replicate the TD position in sprinting in order to maximise the specificity. However the knee ROM from TD to MKF was specific, which as found in Chapter 4 was a defining factor between elite and sub-elite athletes. Furthermore there was a strong velocity specificity of this phase of the BSq_{drop} and thus transfer to sprinting is maximised. The GRF traces of the BSq_{drop} and sprinting were similar as both displayed a double peak of Fz. Whilst the time of ground contact (and thus impulse) were not specific, the peak Fz, average Fz, force over 100ms and peak RFD were specific between the BSq_{drop} and sprinting. The BSq_{drop} was specific in the type, magnitude and rate of loading and thus warrants its inclusion in the strength programme of elite sprinters. The deadlift lacked specificity with respect to the body positions, however the average and maximum knee angular velocities were comparable thus indicating an element of velocity specificity. Velocity specificity is deemed to be crucial to maximise the transfer of effects from strength training to the skill in question. Previous research has found a strong correlation between maximum leg strength and speed (Baker & Nance, 1999) it warrants the inclusion of a deadlift in the training programme of elite sprinters, but perhaps should see more of a focus in the general strength phase of the training programme at the start of the training season. It is concluded both the deadlift and BSq_{drop} are relevant strength training exercises for maximal velocity sprinting, however positional changes should be introduced in order to maximise the specificity to sprinting.

The results indicate the three drills selected for analysis all display some degree of specificity to sprinting. The scissor drill reflected the positions and technique of sprinting whilst the A and B skip better reflect the joint angular velocities of sprinting and coordination strategies as whole. The B skip is favourable to the A skip as it replicates the knee angles of sprinting in addition to the joint angular velocities. Harrison and Warden (2003) stressed that coaches need to question whether drills are producing the desired effect. For example Mann (1987) identified that bounding drills commonly employed to develop vertical velocity are not replicating the ground contact times of sprinting and thus the drill is void. The focus of the A skip is the high knee lift, however the results show a greater degree of knee lift is actually achieved in the B skip. In contrast the focus of the B skip is the foreleg reach and the pawing action towards the ground, which is achieved as the knee angles replicate those of sprinting. Furthermore the hip angular velocities display a good degree of similarity to those in sprinting and thus the drill is achieving its aim. Brady and Maraj (1999) concluded the straight-leg bound is inappropriate for enhancement of the movement pattern of sprinting as the focus of the drill is forward action of the legs away from the body, yet the drill fails to replication the hip angles of sprinting. Perhaps more importantly the authors stress the drills may in fact be dangerous due to the stress placed on the gluteal and hamstring muscles as a result of the lack of knee flexion. Gambetta (2012) suggested that the primary benefit of drills is not as technique drills, rather they are drills to train the muscles in postures similar to those that occur during the sprint action, and through this technique is subsequently improved. Thus it is important that drills are properly taught and executed. The belief that drills lead to more efficient neuromuscular patterns has been advocated by a number of authors (e.g. Dare (1994), Bell (1995), McFarlane (1994)). It has been suggested that the effectiveness of drills will change depending on the performers stage of learning. As the athletes used in the current study were elite performers a high degree of specificity within the drills is important in order to maximise the transference to performances.

6.5 Chapter summary

In order to answer research question *v. – how can specificity be quantified holistically based on biomechanical movement principles?* this chapter began by developing a framework to quantify the specificity of training methods to a movement skill which was validated using a sample of S&C coaches. Using this framework the specificity of the deadlift and BSq_{drop}, followed by running drills to maximal velocity sprinting was investigated. Data were collected from international athletes within the training environment to maximise the external validity of the findings in order to answer research question *vi. – what is the biomechanical specificity of training methods to maximal velocity sprinting?*

An initial exercise which asked coaches to rank a number of strength exercises based on their specificity to maximal velocity sprinting revealed a variance in coaches opinion of training specificity. This was attributed to a lack of consistency in variables considered for specificity, with some coaches focus purely on coordination specificity with no reference to the loading principles of the exercises. Thus a framework was developed to outline the speed, loading, coordination and balance principles that should be considered to develop a holistic view of specificity. The detailed kinematics and kinetics of a BSq_{drop} and deadlift can be used to revisit the MSF and calculate a revised MSR based on the observed specificity in speed, coordination and loading principles. The three running drills investigated all displayed strong coordination specificity to maximal velocity sprinting, thus warranting their inclusion in the training programmes of elite sprinters. The MSF can be used by coaches to ensure a training programme of elite sprinters includes exercises to target all movement principles of a target skill to a high association level.

CHAPTER 7 – DISCUSSION

7.1 Introduction

The aim of this thesis was firstly to establish the kinematics and kinetics associated with elite maximal velocity sprinting at velocities >10.0m/s. Following this a framework to quantify biomechanical specificity was developed and then used to quantify the biomechanical specificity of common training methods adopted by elite sprinters. The research questions outlined in Chapter 1 were utilised to direct the thesis in achieving this aim. The six research questions are revisited in this chapter to outline how they were addressed by Chapters 3 to 6, and to summarise the key findings of this thesis. Following this potential future investigations will be proposed.

7.2 Addressing the research questions

When working within an applied sporting environment the equipment and procedures available to a coach and biomechanist are restricted. Collecting data from competition provides a unique opportunity to investigate elite athletes performing at their peak level. Elite athletes are often unwilling to change their training for the sake of research and thus data collection methods must be non-invasive and not interfere with the execution of the training session/competition. A number of data collection methods are available, and are often used interchangeably between training and competition. Before they can be used to associate technique with performance their reliability and validity must be established. This led to the first research question:

i. *What are the most appropriate measures for analysing the kinematics of maximal velocity sprinting and the associated training methods?*

In Chapter 3, fifteen athletes completed three sprint trials and the temporal-spatial variables associated with maximal velocity sprinting (based on the research reviewed in Chapter 2) were calculated using four different methods. Bland-Altman plots (Bland & Altman, 1986) were used to assess the agreement between the different methods of measurement. The results indicated a high level of agreement between methods, thus concluding techniques can be used interchangeably. The selection of the most appropriate method must therefore be based on the benefits and limitations of the equipment along with the restraints imposed by the environment. In most cases the aim is to improve competitive performance, and therefore the most valid environment to evaluate an intervention/training programme would be to analyse an athlete within competition. Furthermore coaches prefer technology that can provide immediate data as it facilitates the use of objective feedback as opposed to a reliance on subjective feedback. The LDM (Laveg) is favoured for the identification of horizontal velocity due to the high frequency of the measure and the lack of post-processing time, and high-speed cameras are preferential due to the ability to obtain a full COM profile alongside the key performance variables of sprint velocity. Due to the high external validity of such data collection protocols it is possible to relate specific aspects of technique to performance, thus leading to the second research question:

ii. Which kinematic variables are associated with elite levels of maximal velocity sprinting?

Very little research is available describing the technique of elite maximal velocity sprinting at velocities exceeding >10.0m/s due to the difficulty gaining access to elite level athletes. The data collected in Chapter 4 of ten international-level (elite) sprinters and ten national-level (sub-elite) sprinters allowed the technique variables inherent to sprint velocities exceeding 10.0m/s to be established. The fastest velocity observed (12.25m/s) far exceeds those currently reported in the academic literature. The inclusion of elite and sub-elite samples allows the identification of variables which are characteristic of sprint performances >9.0m/s, and the variables which distinguish those performances to performances >10.0m/s. The a-priori approach used in this thesis used a deterministic model of sprinting to provide a systematic basis for the selection of appropriate biomechanical variables. Using this a-priori approach an in-depth kinematic analysis was performed which quantified the joint angles, angular velocities and COM profile of elite maximal velocity sprinting. The research progressed to provide an insight into the lower limb joint coupling motions of sprint running to enhance understanding of the task-specific movement patterns associated with high level sprint performance.

Elite athletes minimised the touchdown distance relative to the COM by increasing the hip and knee angles at TD. Elite athletes minimised the ground contact time by limiting the flexion of the knee and ankle angles during stance, which facilitates the storage of energy in the joints via the SSC cycle. Interestingly sub-elite athletes experienced a significantly higher peak knee extension velocity (450°/s) than elite athletes, which had a strong correlation to velocity (r=0.537), suggesting a minimal velocity is favourable. It is hypothesised the high knee extension velocity experienced by sub-elite athletes may be necessity to overcome the greater range of flexion at MS rather than a performance benefit. Elite athletes terminated ground contact time early by limiting the degree of hip and knee extension at TO. This is in contrast to the previous theories of triple extension advocated by sprint and strength and conditioning coaches alike. Minimising the extension reduces the distance the COM must travel during stance, thus decreasing the GCT and maximising SF. Furthermore it is proposed the early termination of the ground contact allows a more effective swing phase in elite athletes. The addition of the swing limb in the kinematic analysis is a novel aspect of the current thesis and allows a more holistic evaluation of maximal velocity sprinting. The position of the swing limb at the point of TD of the stance limb was a distinguishing feature between elite and sub-elite sprinters. Elite athletes had a significantly smaller thigh angle at TD, which is illustrative of the swing limb being further forward in its swing phase. In addition to this elite athletes reached a greater maximum degree of hip flexion in swing compared to sub-elite athletes. This supports the theory of front side mechanics pioneered by Mann (2010) that better sprinters minimise movements that occur behind the body (i.e. minimise extension at TO) and maximise the movements that occur in front of the body (i.e. maximise flexion in swing).

In order to identify the causes behind these kinematic aspects of technique based on the biomechanical principles proposed a kinetic analysis of maximal velocity sprinting was undertaken in order to answer the next research question:

iii. *Which kinetic variables are associated with elite levels of maximal velocity sprinting?*

The GRF acting on sprinter is a major determinant of sprint performance (Morin et al., 2011). However the majority of this research focuses on slow to moderate velocities (1.5-6.5m/s), with very little research targeted at the elite level (>10.0m/s). To the authors knowledge this is the first in-field research to investigate the kinetics of overground maximal velocity running in a sample of elite athletes. The deterministic model in Chapter 2 depicted how the kinematic variables are influenced by the GRF components and allowed an a-priori approach for the selection of variables to be utilised. The mean peak Fz was 3176N (3.69BW) and the greatest Fz recorded (4449N/4.89BW) was observed in the fastest (11.26m/s) trial which agrees with the notion proposed by Weyand et al. (2000) that greater running speeds are associated with greater vertical GRF. This trial is the fastest sprint trial for which kinetics have been collected in the literature. At maximal velocity the horizontal velocity from TD to TO should be constant, and thus the net horizontal impulse should be zero. The aim must be to decrease the braking impulse, and subsequently the propulsive impulse necessary to overcome it so that contact time can be minimised. The role of vertical impulse at maximal velocity is still unclear. The mean vertical impulse in the current study was 90.9Ns, which resulted in a 1.03m/s increase in vertical velocity. There was a weak positive relationship between maximal horizontal velocity and relative vertical impulse (r=0.138). It is proposed the weak relationship between vertical impulse and velocity is due to individual differences in SF. The research was progressed further to gain an understanding as to how these kinetic and kinematic parameters are interrelated. The deterministic model developed in Chapter 2 can be used to understand how the kinetic components of force relate to the spatiotemporal variables of maximal velocity sprinting. This led to the fourth research question:

iv. *What are the relationships between the kinematics and kinetics of elite maximal velocity sprinting?*

A within-subject comparison as adopted by Hunter et al. (2005) was used to identify the kinematic differences between a high-braking and low-braking trial using a Wilcoxon signed ranks test. The mean peak braking force for a high braking trial was -1.07BW and for a low braking trial was -0.71BW. The high braking trial was characterised by a longer step length, less hip extension at TD, decreased foot speed relative to the COM and an lower velocity of the swing leg at the point of TD. A similar approach was taken to investigate the kinematics associated with a high and low vertical impulse trial. Whilst vertical impulse was not significantly correlated to horizontal velocity it displayed a strong correlation to SL (r=0.518) and SF (r=0.573) which as illustrated by the deterministic model are the two main components of horizontal velocity. The lack of significant difference to horizontal velocity as a whole was attributed to the individual difference in SL and SF reliance (Salo et al., 2011). Both the hip and knee angles at TO were greater (more extension) in the low vertical impulse trials. The findings of Chapter 4 concluded that triple extension of the lower limbs at TO was disadvantageous as it lengthened the ground contact time. Thus it might be expected this triple extension would be associated with a higher vertical impulse due to the increase in time over which force can be applied. However these findings illustrate that the increase in ground contact time does not actually favour the stride as no extra vertical impulse is generated. Research shows that sprinters start reducing their force production once the support knee passes under the hip (Mann, 1985). Athletes should minimise the extension of the hip and knee at TO in order to maximise the vertical impulse and reduce the GCT. A Wilcoxon signed ranks test between a high vertical impulse and low vertical impulse trial indicated that a high vertical impulse trial was typified by a smaller MHF angle (more flexion) of the swing leg.

The kinematic and kinetic technical models developed in this thesis describe the characteristics inherent to elite maximal velocity sprinting. A better understanding of the factors that limit performance at maximal velocity enables coaches to design the training programmes to overcome these limitations. It is well acknowledged that the transference of training to competitive performance is enhanced when training is specific to the end goal (Stone et al., 2000). However training specificity is often misinterpreted by coaches with no consideration of specificity in the coordination and loading principles of a skill. This led to the fifth research question:

v. *How can specificity be quantified holistically based on biomechanical movement principles?*

The nature of specificity has received attention in the strength and conditioning literature with regards to exercise selection, yet this tends to be restricted to the notion of movement pattern specificity. Both Gamble (2006) and Graham-Smith et al. (2010) stressed that specificity of training should not be solely restricted to reflecting the movement patterns of the skill, but should also incorporate the specificity of the coordination, speed, loading and balance principles of the skill itself. The interpretation of biomechanical specificity is varied between coaches and is based on subjective opinion with no scientific research available to quantify specificity.

A movement specificity framework (MSF) was developed to facilitate the quantification of biomechanical specificity. The MSF provided a means by which specificity can be investigated holistically based on a number of biomechanical principles (speed, loading, coordination and balance). The movement specificity ratio (MSR) is a quantifiable value based on these movement principles of how well a skill replicates the target skill. The MSF can be used by coaches to ensure a training programme of elite sprinters includes exercises to target all movement principles of a target skill to a high association level. The MSR illustrated that based on movement principles the most specific training methods to maximal velocity sprinting are resisted and supramaximal sprinting. This would be expected as these are the exercises which most closely replicate the action of sprinting. There was discrepancy in the perceived specificity of a Bulgarian split squat and therefore a detailed kinematic and kinetic analysis was undertaken with a sample of elite sprinters. Furthermore the deadlift ranked as ‘low specificity’ so was investigated further to assess its relevance in the training programme of elite sprinters. This led to the final research question:

vi. What is the biomechanical specificity of training methods to maximal velocity sprinting?

At the point of TD both the hip and knee angle were more flexed in the BSq_{drop} than sprinting. Research provides strong evidence for joint angle training specificity which can extend to a range of 20° either side of the training angle (Knapik et al., 1983). Thus it is proposed that despite the 18° and 24° difference of the hip and knee angles respectively at TD may still be within a range at which joint angle specificity may apply. Importantly the knee ROM from TD to MKF was similar between the BSq_{drop} (-10°) and maximal velocity sprinting (-14°). The findings in Chapter 4 found elite athletes minimised knee flexion during stance and that knee angle at MKF was strongly correlated to horizontal velocity (r=0.437). Thus reducing knee flexion is advantageous to attaining maximal horizontal velocity, and by reproducing this element in the BSq_{drop} this may then transfer to maximal sprinting. Based on the movement principles the BSq_{drop} had a high level of specificity in the loading principles as it entails a fore acceptance phase of an eccentric muscle contraction following impact. Visual inspection of a GRF trace for a BSq_{drop} and maximal velocity sprinting indicated similar force profiles as both traces exhibited a double peak in Fz. The maximum FZ in a BSq_{drop} was 3416N (3.92BW) in comparison to the 3162N (3.68BW) in maximal sprinting. Based on the training principle of overload (Dick, 1980) the larger musculoskeletal work performed by the lower limb during the BSq_{drop} may produce specific muscular and neurological adaptations that facilitate an improvement in sprint performance. The maximum rate of force development was greater in the BSq_{drop} than sprinting, but was not significantly different and thus it can be concluded it is specific. The BSq_{drop} was specific in the type, magnitude and rate of loading and thus warrants its inclusion in the strength programme of elite sprinters.

The deadlift lacked specificity with regard to the joint angles and angular velocities of maximal sprinting. Young et al. (2001b) classified the deadlift as a ‘nonspecific’ exercise for maximum speed sprinting. However research has supported a significant relationship between maximum leg strength and sprinting speed (Baker & Nance, 1999), and thus the deadlift still has a role within a resistance-training programme. It should be considered a deadlift may be included in a strength program in order to target the characteristics of the start and acceleration phases. An improvement in the acceleration phase may allow an athlete to reach higher speeds in the maximal velocity phase.

Running drills are utilised to develop the optimal movement and coordination patterns of sprinting (Harrison, 2010), however scientific research is yet to establish whether running drills actually replicate the coordination patterns of maximal velocity sprinting. Both the A and B skip over exaggerate the high knee position (MHF) in comparison to sprinting. Chapter 4 identified the degree of MHF as a technical indicator between elite and sub-elite athletes where a greater degree of MHF is favourable to performance. Thus the over exaggeration in the drills may lead to a positive transfer to sprint performance. Both the A and B skip displayed hip and knee angles at TD within 10° of maximal velocity sprinting. Kitai and Sale (1989) concluded joint angle specificity in training methods extended to 10° either side of the joint and therefore the TD position can be deemed as specific to sprinting. The coaching focus of the three drills investigated was the rapid acceleration of the lower limb in the latter phases of the swing. The peak and average hip and ankle extension velocities were specific between the A and B skip and maximal velocity sprinting. The angle-angle plots offered an approach by which to fully investigate the coordination specificity between the drills and maximal velocity sprinting. Both the A and B skip employed similar coordination strategies to maximal sprinting with only the absolute magnitude of the angles differing. The scissor drills lacked specificity in coordination strategies due to the lack of knee flexion and extension. All three drills investigated are cyclical in nature, conducted in postures similar to sprinting and are unilateral exercises, and thus display a strong degree of movement coordination specificity to sprinting.

7.3 Future investigations

The investigations undertaken in this thesis have furthered the understanding of elite maximal velocity sprint performance and the biomechanical specificity of training methods. However this has highlighted a number of areas for future research. Whilst the separate analyses of kinematic and kinetics of truly elite levels of sprint performance has never been conducted before, the addition of inverse dynamics would provide understanding into the joint kinetics associated with elite sprinting.

However it is stressed that in order to maintain the extremely high external validity of the findings that this be performed at velocities representative of those of elite athletes, at the maximal velocity phase of sprinting and near the competitive phase of the season. Similarly the inclusion of EMG would add to the understanding of elite sprint technique but is problematic without interference to elite athletes.

The thesis developed a novel approach by which to quantify the biomechanical specificity of training methods based on movement principles, and takes into account the relative importance of each movement principles to the overall task outcome. Further research could apply the MSF to a greater range of sprint training exercises, in particular strength training exercises that are used within the specific phase of a periodised training programme for example the power clean, snatch and derivatives. Moreover, further evaluation of whether the MSR can act as a planning tool to judge exercise specificity throughout a periodised training programme is warranted.

A limitation of the present study was the absence of EMG to evaluate the training exercises considered in Chapter 6. The inclusion of EMG in the analysis of training exercises would help evaluate whether such exercises are targeting the same muscle groups of maximal velocity sprinting. Future studies should include EMG analysis to aid future evaluations of the specificity of training exercises in relation to the MSF.

7.4 Thesis conclusion

The aim of the thesis was to gain understanding into the kinematics and kinetics of maximal velocity sprint running in elite sprinters. Further a framework for the quantification of biomechanical specificity was developed and utilised to discuss the specificity of some common sprint training methods utilised by elite sprinters. Six research questions were developed to achieve this objective, and these questions were answered through a series of empirical investigations utilising elite athletes. Analysis of kinematic data of international-level sprinters identified several technique variables which were inherent to achieving sprint velocities >10.0m/s. Further a kinetic analysis of sprint velocities exceeding 9.0m/s identified the relationships between the GRF trace and key kinematic variables of maximal velocity running. A method was established by which to quantify the biomechanical specificity of training methods, and an in-depth analysis of running drills and strength exercises indicated high levels of both kinematic and kinetic specificity amongst these methods. This thesis has identified the critical aspects of maximal velocity sprint technique in elite athletes and how sprint training methods can maximise their degree of specificity to improve them.

APPENDIX

Table 8-1 Example of MSF for Bulgarian split squat

MOVEMENT PRINCIPLES	*IMP.*	*ASSOC.*	*MSS*
1. Speed Principles			
Whole Body Speed			
Is the exercise similar with respect to horizontal speed?	2	1	2
Is the exercise similar with respect to vertical speed?	1	2	2
Is the exercise similar with respect to rotation speed	0	0	0
Contact / Movement time			
Is the exercise similar with respect to time in contact with the ground or execution time?	2	1	2
2. Loading Principles			
Type of loading			
Force Acceptance (eccentric muscle contraction following impact)	2	3	6
Force Acceptance (eccentric muscle contraction without impact)	0	0	0
Force Generation (active isometric muscle contraction)	2	2	4
Force Generation (active concentric muscle contraction)	2	0	0
Magnitude of Load			
Does the exercise elicit similar or greater vertical ground reaction forces?	2	3	6
Does the exercise elicit similar or greater horizontal ground reaction forces?	2	2	4
Rate of Loading			
Is the rate of loading similar in force acceptance?	2	3	6
Is the rate of force development similar?	2	0	0
3. Movement Coordination Principles			
Force - Length			
Do the joints go through similar ranges of motion?	2	2	4
Force - Velocity			
Do the joints move at similar angular velocities?	2	2	4
Stretch-Shorten Cycle			
Do the muscles crossing joints undergo a stretch-shorten cycle?	2	0	0
Symmetry			
Is the movement unilateral or bilateral?	2	3	6
Sequential movements			
Does the movement involve a kinetic chain from proximal to distal segments?	1	0	0
Muscle Relaxation			
Is the skill a cyclical movement?	2	0	0
If Yes, does the movement help to relax antagonists when agonists are working?	2	0	0
4. Balance Principles			
Support / Balance			
Does the exercise challenge proprioception and balance for control?	2	3	6
	34		52
Maximum available score (sum of importance rating x 3)	102	**MSR**	**0.51**

REFERENCES

Aagaard, P., Simonsen, E. B., Andersen, J. L., Magnusson, P., & Dyhre-Poulsen, P. (2002). Increased rate of force development and neural drive of human skeletal muscle following resistance training. *Journal of Applied Physiology, 93*(4), 1318-1326.

Ae, M., Ito, A., & Suzuki, M. (1992). The men's 100 metres. *New Studies in Athletics, 7*, 47-52.

Ali, N., Rouhi, G., & Robertson, G. (2013). Gender, Vertical Height and Horizontal Distance Effects on Single-Leg Landing Kinematics: Implications for Risk of non-contact ACL Injury. *Journal of Human Kinetics, 37*, 27-38.

Altman, D. G., & Bland, J. M. (1991). Improving doctors understanding of statistics. *Journal of the Royal Statistical Society Series a-Statistics in Society, 154*, 223-267.

Arampatzis, A., Bruggemann, G. P., & Metzler, V. (1999). The effect of speed on leg stiffness and joint kinetics in human running. *Journal of Biomechanics, 32*(12), 1349-1353.

Arsac, L. M., & Locatelli, E. (2002). Modeling the energetics of 100-m running by using speed curves of world champions. *Journal of Applied Physiology, 92*, 1781-1788.

Atkinson, G., & Nevill, A. M. (2001). Selected issues in the design and analysis of sport performance research. *Journal of Sports Sciences*, *19*(10), 811-827.

Baechle, T., Earle, R., & Wahten, D. (2000). *Essentials of strength training and conditioning*. Champaign, IL: Human Kinetics.

Baker, D., & Nance, S. (1999). The relation between running speed and measures of strength and power in professional rugby league players. *The Journal of Strength & Conditioning Research, 13*(3), 230-235.

Baumgartner, T. A., & Chung, H. (2001). Confidence limits for intraclass reliability coefficients. *Measurement in Physical Education and Exercise Science, 5*(3), 179-188.

Behm, D. G., & Sale, D. G. (1993). Intended rather than actual movement velocity determines velocity-specific training response. *Journal of Applied Physiology, 74*(1), 359-368.

Bell, S. (1995). Drills which lead to better sprint performance. *US Track Coaches Review, 95*(1), 13-15.

Belli, A., Kyrolainen, H., & Komi, P. L. V. (2002). Moment and power of lower limb joints in running. *International Journal of Sports Medicine, 23*(2), 136-141.

Bezodis, I., Salo, A., & Kerwin, D. G. (2007). *Joint kinetics in maximum velocity sprint running.* Paper presented at the Proceedings of the XXV International Conference on Biomechanics in Sports, Brazil.

Bezodis, I., Salo, A., & Kerwin, D. G. (2009). *Athlete-specific analyses of leg joint kinetics during maximum velocity sprint running.* Paper presented at the Proceedings of the XXVII International Conference on Biomechanics in Sports, University of Limerick, Ireland.

Bezodis, I. N., Kerwin, D. G., & Salo, A. I. T. (2008). Lower-limb mechanics during the support phase of maximum-velocity sprint running. *Medicine and Science in Sports and Exercise, 40*(4), 707-715.

Bezodis, N. E. (2009). *Biomechanical investigations of sprint start technique and performance.* (PhD), University of Bath, Bath.

Bland, J. M., & Altman, D. G. (1986). Statistical methods for assessing agreement between 2 methods of clinical measurement. *Lancet, 1*(8476), 307-310.

Blazevich, A. J., & Jenkins, D. G. (2002). Effect of the movement speed of resistance training exercises on sprint and strength performance in concurrently training elite junior sprinters. *Journal of Sports Sciences, 20*(12), 981-990.

Bobbert, M. F., & van Ingen Schenau, G. J. (1990). Mechanical output about the ankle joint in isokinetic plantar flexion and jumping. *Medicine & Science in Sports & Exercise, 22*, 660-668.

Bosch, F., & Klomp, R. (2005). *Running: Biomechanics and exercise physiology in practice*. Maarssen, The Netherlands: Elsevier Churchill Livingstone.

Bosquet, L., Berryman, N., & Dupuy, O. (2009). A comparison of 2 optical timing systems designed to measure flight time and contact time during jumping and hopping. *Journal of Strength and Conditioning Research, 23*(9), 2660-2665.

Bradshaw, E. J., Maulder, P. S., & Keogh, J. W. L. (2007). Biological movement variability during the sprint start: Performance enhancement or hindrance? *Sports Biomechanics, 6*(3), 246-260.

Brady, S., & Maraj, B. K. V. (1999). Testing straight leg bounds as a drill for sprinting. *Track Coach, 146*, 1-2.

Brown, E. W., & Abani, K. (1985). Kinematics and kinetics of the dead lift in adolescent power lifters. *Medicine and Science in Sports and Exercise, 17*(5), 554.

Brughelli, M., Cronin, J., & Chaouachi, A. (2011). Effects of running velocity on running kinetics and kinematics. *Journal of Strength & Conditioning Research, 25*(4), 933-939.

Butler, R. J., Crowell, H. P., & Davis, I. M. (2003). Lower extremity stiffness: implications for performance and injury. *Clinical Biomechanics, 18*(6), 511-517.

Campbell, K. L., Neil, S. E., & Winters-Stone, K. M. (2012). Review of exercise studies in breast cancer survivors: attention to principles of exercise training. *British Journal of Sports Medicine, 46*(13), 909-U930.

Canavan, P. K., Garrett, G. E., & Armstrong, L. E. (1996). Kinematic and kinetic relationships between an Olympic-style lift and the vertical jump. *The Journal of Strength & Conditioning Research, 10*(2), 127-130.

Cappa, D. F., & Behm, D. G. (2011). Training specificity of hurdle vs. countermovement jump training. *Journal of Strength & Conditioning Research, 25*(10), 2715-2720.

Cavagna, G. A., Komarek, L., & Mazzolen, S. (1971). Mechanics of sprint running. *Journal of Physiology, 217*(3), 709-&.

Challis, J. H. (2001). The variability in running gait caused by force plate targeting. *Journal of Applied Biomechanics, 17*(1), 77-83.

Chapman, A. E., & Caldwell, G. E. (1983). Kinetic limitations of maximal sprinting speed. *Journal of Biomechanics, 16*(1), 79-83.

Chow, J. W., & Knudson, D. V. (2011). Use of deterministic models in sports and exercise biomechanics research. *Sports Biomechanics, 10*(3), 219-233.

Chumanov, E. S., Heiderscheit, B. C., & Thelen, D. G. (2007). The effect of speed and influence of individual muscles on hamstring mechanics during the swing phase of sprinting. *Journal of Biomechanics, 40*(16), 3555-3562.

Coh, M., Jost, B., Skof, B., Tomazin, K., & Dolenec, A. (1998a). Kinematic and kinetic parameters of the sprint start and start acceleration model of top sprinters. *Gymnica, 28*, 33-42.

Coh, M., Jost, B., & Stuhec, S. (1998b). Kinematic and dynamic structure of the sprinting stride of top female sprinters. *Biology of Sport, 15*(4), 237-243.

Coh, M., & Mackala, K. (2013). Differences between the elite and subelite sprinters in kinematic and dynamic determinations of countermovement jump and drop jump. *Journal of Strength and Conditioning Research, 27*(11), 3021-3027.

Coh, M., Mihajlovic, S., & Praprotnik, U. (2001). Morphologic and kinematic characteristics of elite sprinters. *Acta Kinesiologiae Universitatis Tartuensis, 6*(Suppl), 100-103.

Cohen, J. W. (1988). *Statistical power analysis for the behavioural sciences* (2nd ed.). Hillsdale, NJ: Lawrence Erlbaum Associates.

Comfort, P., Allen, M., & Graham-Smith, P. (2011). Comparisons of peak ground reaction force and rate of force development during variations of the power clean. *The Journal of Strength & Conditioning Research, 25*(5), 1235-1239.

Cook, C. J., Crewther, B. T., & Smith, A. A. (2012). Comparison of baseline free testosterone and cortisol concentrations between elite and non-elite female athletes. *American Journal of Human Biology, 24*(6), 856-858.

Cormie, P., McGuigan, M. R., & Newton, R. U. (2010). Adaptations in Athletic Performance after Ballistic Power versus Strength Training. *Medicine and Science in Sports and Exercise, 42*(8), 1582-1598.

Coyle, E. F., Feiring, D. C., Rotkis, T. C., Cote, R. W., Roby, F. B., Lee, W., & Wilmore, J. H. (1981). Specificity of power improvements through slow and fast isokinetic training. *Journal of Applied Physiology, 51*(6), 1437-1442.

Dare, B. (1994). Technique analysis: an overview of running mechanics. *Track Technique, 87*, 2834-2836.

de Leva, P. (1996). Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *Journal of Biomechanics, 29*(9), 1223-1230.

de Villarreal, E. S., Requena, B., & Cronin, J. B. (2012). The effects of plyometric training on sprint performance: a meta-analysis. *Journal of Strength and Conditioning Research, 26*(2), 575-584.

Delecluse, C. (1997). Influence of strength training on sprint running performance - Current findings and implications for training. *Sports Medicine, 24*(3), 147-156.

Dempster, W. T. (1955). Space requirements of the seated operator. *US Air Force WADC Technical Report, 1*, 55-159.

DeVita, P. (1994). The selection of a standard convention for analyzing gait data based on the analysis of relevant biomechanical factors. *Journal of Biomechanics, 27*(4), 501-508.

Dick, F. W. (1980). *Sports training principles*. London: Lepus Books

Dick, F. W. (1989). Development of maximum sprinting speed. *Track Coach, 109*.

Dierks, T. A., & Davis, I. (2007). Discrete and continuous joint coupling relationships in uninjured recreational runners. *Clinical Biomechanics, 22*(5), 581-591.

Duthie, G. M., Pyne, D. B., Marsh, D. J., & Hooper, S. L. (2006). Sprint patterns in rugby union players during competition. *The Journal of Strength & Conditioning Research, 20*(1), 208-214.

Eliasziw, M., Young, S. L., Woodbury, M. G., & Fryday-Field, K. (1994). Statistical methodology for the concurrent assessment of interrater relaibility: using goniometric measurements as an example. *Physical Therapy, 74*, 777-788.

Elliott, B., Lyttle, A., & Birkett, O. (2002). The RowPerfect ergometer: a training aid for on-water single scull rowing. *Sports biomechanics / International Society of Biomechanics in Sports, 1*(2).

Enoka, R. M. (1997). Neural adaptations with chronic physical activity. *Journal of Biomechanics, 30*(5), 447-455.

Ericsson, K. A., Krampe, R. T., & Tesch-Römer, C. (1993). The role of deliberate practice in the acquisition of expert performance. *Psychological review, 100*(3), 363.

Escamilla, R. F., Francisco, A. C., Fleisig, G. S., Barrentine, S. W., Welch, C. M., Kayes, A. V., . . . Andrews, J. R. (2000). A three-dimensional biomechanical analysis of sumo and conventional style deadlifts. *Medicine & Science in Sports & Exercise, 32*(7), 1265-1275.

Escamilla, R. F., Lowry, T. M., Osbahr, D. C., & Speer, K. P. (2001). Biomechanical analysis of the deadlift during the 1999 Special Olympics World Games. *Medicine & Science in Sports & Exercise, 33*(8), 1345-1353.

Exell, T. A. (2010). *Lower-limb biomechanical asymmetry in maximal velocity sprint running.* (Doctor of Philosophy), University of Wales Institute, Cardiff.

Exell, T. A., Gittoes, M. J. R., Irwin, G., & Kerwin, D. G. (2012). Gait asymmetry: Composite scores for mechanical analyses of sprint running. *Journal of Biomechanics, 45*(6), 1108-1111.

Fauth, M. L., Garceau, L., Lutsch, B., Gray, A., Szalkowski, C., Wurm, B., & Ebben, P. (2010). *Kinetic analysis of lower body resistance training exercises*. Paper presented at the XXVII Congree of the International Society of Biomechanics in Sports.

Fenn, W. O. (1930). Work against gravity and work due to velocity changes in running - Movements of the center of gravity within the body and foot pressure on the ground. *American Journal of Physiology, 93*(2), 433-462.

Fleiss, J. L. (1999). *Design and analysis of clinical experiments* (Vol. 73): John Wiley & Sons.

Fleming, N., Donne, B., Fletcher, D., & Mahony, N. (2012). A biomechanical assessment of ergometer task specificity in elite flatwater kayakers. *Journal of Sports Science and Medicine, 11*(1), 16-25.

Fletcher, I. M. (2009). Biomechanical aspects of sprint running. *UKSCA*(16).

Folland, J. P., Hawker, K., Leach, B., Little, T., & Jones, D. A. (2005). Strength training: Isometric training at a range of joint angles versus dynamic training. *Journal of Sports Sciences, 23*(8), 817-824.

Fry, R. W., Morton, A. R., Garcia-Webb, P., Crawford, G. P., & Keast, D. (1992). Biological responses to overload training in endurance sports. *European Journal of Applied Physiology and Occupational Physiology, 64*(4), 335-344.

Gambetta, V. (1991). Essential considerations for the development of a teaching model for the 100 metres sprint. *New Studies in Athletics, 6*(2), 27-32.

Gambetta, V. (2012). Mach sprint drills - a personal and historical perspective. Retrieved from http://www.gillathletics.com/articles/

Gamble, P. (2006). Implications and applications of training specificity for coaches and athletes. *Strength and Conditioning Journal, 28*(3), 54-58.

Gamble, P. (2010). *Strength and conditioning for team sports: sport-specific physical preparation for high performance*. New York: Routledge.

Garhammer, J. (1985). Biomechanical profiles of Olympic weightlifters. *International Journal of Sport Biomechanics, 1*(2), 122-130.

Gittoes, M. J. R., & Wilson, C. (2010). Intralimb Joint Coordination Patterns of the Lower Extremity in Maximal Velocity Phase Sprint Running. *Journal of Applied Biomechanics, 26*(2), 188-195.

Glatthorn, J. F., Gouge, S., Nussbaumer, S., Stauffacher, S., Impellizzeri, F. M., & Maffiuletti, N. A. (2011). Validity and reliability of optojump photoelectric cells for estimating vertical jump height. *Journal of Strength and Conditioning Research, 25*(2), 556-560.

Glazier, P., & Irwin, G. (2001). *Validity of stride length estimates obtained from Optojump.* Paper presented at the XIXth International Symposium on Biomechanics in Sports.

Goodwin, J. (2011). Maximum velocity is when we can no longer accelerate. *Using biomechanics to inform speed development. Professional Strength Cond, 21*, 3-9.

Gourgoulis, V., Aggeloussis, N., Vezos, N., & Mavromatis, G. (2006). Effect of two different sized hand paddles on the front crawl stroke kinematics. *Journal of Sports Medicine and Physical Fitness, 46*(2), 232-237.

Grabiner, M. D., & Garhammer, J. (1989). *Analysis and assessment of human movement performance*. Philadelphia: Lea & Febiger.

Graham-Smith, P., Comfort, P., Jones, P., & Matthews, M. (2010). Movement specificity - what does it mean? *Professional Strength and Conditioning, 24*, 10-12.

Graham-Smith, P., Jones, P., Comfort, P., & Matthews, M. (2008, 10th December 2008). *The use of biomechanics and performance analysis in strength and conditioning.* Paper presented at the BASES workshop, University of Salford, United Kingdom.

Graves, J. E., Pollock, M. L., Jones, A. E., Colvin, A. B., & Leggett, S. H. (1989). Specificity of limited range of motion variable resistance training. *Medicine and Science in Sports and Exercise, 21*(1), 84.

Grimshaw, P. N., Marar, L., Salo, A., Knight, G., & Vernon, J. (1995). A kinematic analysis of sprint hurdles training strategies (isolation drills). *Athletics Coach, 29*(4), 24-28.

Guimaraes, A. C. S., & Hay, J. G. (1985). A mechanical analysis of the grab starting technique in swimming. *International Journal of Sport Biomechanics, 1*(1), 25-35.

Hales, M. E., Johnson, B., & Johnson, J. T. (2009). Kinematic analysis of the powerlifting style squat and the conventional deadlift during competition: Is there a cross-over effect between lifts? *Journal of Strength & Conditioning Research, 23*(9), 2574-2580.

Hamill, J., Bates, B., Knutzen, K., & Sawhill, J. (1983). Variations in ground reaction force parameters at different running speeds. *Human Movement Science, 2*(1), 47-56.

Hamill, J., van Emmerik, R. E., Heiderscheit, B. C., & Li, L. (1999). A dynamical systems approach to lower extremity running injuries. *Clinical Biomechanics, 14*(5), 297-308.

Harbili, E. (2012). A gender-based kinematic and kinetic analysis of the snatch lift in elite weightlifters in 69-kg category. *Journal of Sports Science and Medicine, 11*(1), 162-169.

Harrison, A. J. (2010). *Biomechanical factors in sprint training - where science meets coaching*. Paper presented at the XXVIII International Symposium of Biomechanics in Sports.

Harrison, A. J., Jensen, R. L., & Donoghue, O. (2005). A comparison of laser and video techniques for determining displacement and velocity during running. *Measurement in Physical Education and Exercise Science, 9*(4), 219-231.

Harrison, D., & Warden, P. (2003). Isolation (sprinting) drills. Retrieved October 2011, from http://www.coachesinfo.com/index.php?option=com_content&view=article&id=355:sprintingdrillarticle&catid=99:track-athletics&Itemid=184

Hay, J. G. (1993). *The biomechanics of sports techniques*. Englewood Cliffs, NJ: Prentice-Hall

Heiderscheit, B. C., Hamill, J., & van Emmerik, R. E. A. (2002). Variability of stride characteristics and joint coordination among individuals with unilateral patellofemoral pain. *Journal of Applied Biomechanics, 18*(2), 110-121.

Henry, F. M. (1968). Specificity vs. generality in learning motor skill. *Classical studies on physical activity*, 328-331.

Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports Medicine, 30*(1), 1-15.

Hopkins, W. G. (2004). How to interpret changes in an athletic performance test. *Sportscience, 8*, 1-7.

Horn, T. (1988). A biomechanical comparison of sumo and conventional deadlifting techniques. *International Journal of Sports Medicine, 9*(2), 150-150.

Hortobagyi, T., Hill, J. P., Houmard, J. A., Fraser, D. D., Lambert, N. J., & Israel, R. G. (1996). Adaptive responses to muscle lengthening and shortening in humans. *Journal of Applied Physiology, 80*(3), 765-772.

Hughes, M., & Franks, I. (2007). *The essentials of performance analysis: an introduction*: Routledge.

Hunter, J. P., Marshall, R. N., & McNair, P. (2004a). Interaction of step length and step rate during sprint running. *Medicine and Science in Sports and Exercise, 36*(2), 261-271.

Hunter, J. P., Marshall, R. N., & McNair, P. (2004b). Reliability of biomechanical variables of sprint running. *Medicine and Science in Sports and Exercise, 36*(5), 850-861.

Hunter, J. P., Marshall, R. N., & McNair, P. (2004c). Segment-interaction of the stance limb in sprint running. *Journal of Biomechanics*, *37*, 1439-1446.

Hunter, J. P., Marshall, R. N., & McNair, P. (2005). Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. *Journal of Applied Biomechanics, 21*(1), 31-43.

Irwin, G., Kerwin, D., Rosenblatt, B., & Wiltshire, H. (2007). *Evaluation of the power clean as a sprint specific exercise.* Paper presented at the ISBS-Conference Proceedings Archive.

Irwin, G., & Kerwin, D. G. (2005). Biomechanical similarities of progressions for the longswing on high bar. *Sports Biomechanics, 4*(2), 163-178.

Ito, A., Fukuda, K., & Kijima, K. (2008). Mid-phase sprinting movements of Tyson Gay and Asafa Powell in the 100-m race during the 2007 IAAF World Championships in Athletics. *New Studies in Athletics, 23*(2), 39-43.

Ito, A., Ichikawa, H., Saito, M., Sagawa, K., Ito, M., & Kobayashi, K. (1998). Relationship between sprint running movement and velocity at full speed phase during a 100m race. *Japan Journal of Physical Education, 43*, 260-273.

Ito, A., Saito, M., Sagawa, K., Kato, K., Ae, M., & Kobayashi, K. (1994). Leg movement analysis of gold and silver medalists in men's 100m at the III World Championships in Athletics. *Journal of Biomechanics, 27*(6), 670-670.

Ives, J. C., & Shelley, G. A. (2003). Psychophysics in functional strength and power training: Review and implementation framework. *Journal of Strength and Conditioning Research, 17*(1), 177-186.

Jarver, J. (1978). Sprinting in a nutshell. *Sprints and Relays 1st Edition. Mountain View, CA: TAFNEWS Press, pg*, 9-13.

Kanehisa, H., & Miyashita, M. (1983). Specificity of velocity in strength training. *European Journal of Applied Physiology and Occupational Physiology, 52*(1), 104-106.

Kawamori, N., & Newton, R. U. (2006). Velocity specificity of resistance training: Actual movement velocity versus intention to move explosively. *Strength and Conditioning Journal, 28*(2), 86-91.

Kawamori, N., Nosaka, K., & Newton, R. U. (2013). Relationships between ground reaction impulse and sprint acceleration performance in team sport athletes. *Journal of Strength and Conditioning Research, 27*(3), 568-573.

Kearney, J. T. (1999). Sport performance enhancement: Design and analysis of research. *Medicine and Science in Sports and Exercise, 31*(5), 755-756.

Kerwin, D. G. (1997). *Force plate analyses of human jumping.* (Doctor of Philosophy), Loughborough University.

Kilding, A. E., Scott, M. A., & Mullineaux, D. R. (2007). A kinematic comparison of deep water running and overground running in endurance runners. *Journal of Strength & Conditioning Research, 21*(2), 476-480.

Kitai, T. A., & Sale, D. G. (1989). Specificity of joint angle in isometric training. *European Journal of Applied Physiology and Occupational Physiology, 58*(7), 744-748.

Kivi, D. M. R. (1997). *A kinematic comparison of the running A and B drills with sprinting.* (Master of Science), The University of Manitoba, Manitoba.

Knapik, J. J., Mawdsley, R. H., & Ramos, M. U. (1983). Angular specificity and test mode specificity of isometric and isokinetic strength training. *The Journal of Orthopaedic and Sports Physical Therapy, 5*(2), 58-65.

Kolar, E., Kolar, K. A., & Stuhec, S. (2002). Comparative analysis of selected biomechanic characteristics between a support backward swing and support swing for the 1 1/4 straddle-piked forward salto on the parallel bars. *Sports Biomechanics, 1*(1), 69-78.

Korchemny, R. (1994). Speed development training menu. *Track Technique, 129*, 105-110.

Korhonen, M. T., Suominen, H., Viitasalo, J. T., Liikavainio, T., Alen, M., & Mero, A. A. (2010). Variability and symmetry of force platform variables in maximum-speed running in young and older athletes. *Journal of Applied Biomechanics, 26*(3), 357-366.

Kraemer, W. J., Ratamess, N. A., & French, D. N. (2002). Resistance training for health and performance. *Current Sports Medicine Reports, 1*(3), 165-171.

Kristianslund, E., Krosshaug, T., & van den Bogert, A. J. (2012). Effect of low pass filtering on joint moments from inverse dynamics: implications for injury prevention. *Journal of Biomechanics, 45*(4), 666-671.

Krzysztof, M., & Mero, A. (2013). A kinematics analysis of three best 100 m performances ever. *Journal of Human Kinetics, 36*(1), 149-160.

Kuitunen, S., Komi, P. V., & Kyrolainen, H. (2002). Knee and ankle joint stiffness in sprint running. *Medicine and Science in Sports and Exercise, 34*(1), 166-173.

Kunz, H., & Kaufmann, D. A. (1981). Biomechanical analysis of sprinting: decathletes versus champions. *British Journal of Sports Medicine, 15*, 177-181.

Kurz, M. J., & Stergiou, N. (2002). Effect of normalization and phase angle calculations on continuous relative phase. *Journal of Biomechanics, 35*(3), 369-374.

Kyrolainen, H., Komi, P. V., & Belli, A. (1999). Changes in muscle activity patterns and kinetics with increasing running speed. *Journal of Strength and Conditioning Research, 13*(4), 400-406.

Larkins, C. (1987). The take-off drill for the long jump. *Track Coach, 107*.

Lauder, M., & Payton, C. (1995). Handle paddle in swimming: A specific form of resistance training. *Swimming Times, 72*(12), 25-27.

Lees, A. (1999). Biomechanical assessment of individual sports for improved performance. *Sports Medicine, 28*(5), 299-305.

Lees, A. (2002). Technique analysis in sports: a critical review. *Journal of Sports Sciences, 20*(10), 813-828.

Leirdal, S., Roeleveld, K., & Ettema, G. (2008). Coordination specificity in strength and power training. *International Journal of Sports Medicine, 29*(3), 225-231.

Lockie, R. G., Murphy, A. J., Schultz, A. B., Jeffriess, M. D., & Callaghan, S. J. (2013). Influence of Sprint Acceleration Stance Kinetics on Velocity and Step Kinematics in Field Sport Athletes. *Journal of Strength and Conditioning Research, 27*(9), 2494-2503.

Luhtanen, P., & Komi, P. (1978). Mechanical factors influencing running speed. *Biomechanics VI-B*, 23-29.

Makaruk, H., & Sacewicz, T. (2011). The effect of drop height and body mass on drop jump intensity. *Biology of Sport, 28*(1), 63-67.

Mann, R. (1985). Biomechanical analysis of the elite sprinter and hurdler. In N. K. Butts, T. T. Gushiken & B. Zarins (Eds.), *The Elite Athlete*. Champaign, Illinois: Life Enhancement Publications.

Mann, R. (1986). The biomechanical analysis of sprinters. *Track Technique, 94*, 3000-3003.

Mann, R. (1987). *The biomechanical analysis of sprinters*. Paper presented at the USOC/TAC Elite Conference, Colorado Springs.

Mann, R. (2010). *The mechanics of sprinting and hurdling*: Independent Publishing Platform.

Mann, R., & Herman, J. (1985). Kinematic analysis of Olympic sprint performance: Men's 200 meters. *International Journal of Sport Biomechanics, 1*(2), 151-162.

Mann, R., Kotmel, J., Herman, J., Johnson, B., & Schultz, C. (1984). Kinematic trends in elite sprinters *In, Terauds, J. (ed.) et al., Sports biomechanics. Proceedings of ISBS 1984, Del Mar, Calif., Research Center for Sports, c1984, p. 17-33.* United States.

Mann, R., & Sprague, P. (1980). A kinetic analysis of the ground leg during sprint running. *Research Quarterly for Exercise and Sport, 51*(2), 334-348.

Mann, R. V. (1981). A kinetic analysis of sprinting. *Medicine and Science in Sports and Exercise, 13*(5), 325-328.

McBride, J. M., Triplett-McBride, T., Davie, A., & Newton, R. U. (2002). The effect of heavy- vs. light-load jump squats on the development of strength, power, and speed. *Journal of Strength and Conditioning Research, 16*(1), 75-82.

McDonagh, M., & Davies, C. (1984). Adaptive response of mammalian skeletal muscle to exercise with high loads. *European Journal of Applied Physiology and Occupational Physiology, 52*(2), 139-155.

McFarlane, B. (1994). Speed...a basic and advanced technical model. *Track Technique, 126*, 4016-4020.

McGuigan, M. R., & Wilson, B. D. (1996). Biomechanical analysis of the deadlift. *The Journal of Strength & Conditioning Research, 10*(4), 250-255.

McKenna, M., & Riches, P. E. (2007). A comparison of sprinting kinematics on two types of treadmill and over-ground. *Scandinavian Journal of Medicine & Science in Sports, 17*(6), 649-655.

McLaughlin, T. M., Dillman, C. J., & Lardner, T. J. (1977). A kinematic model of performance in the parallel squat by champion powerlifers. *Medicine and Science in Sports and Exercise*, *9*(2), 128.

McNab, T. (2006). *Sports Coaching: coaches should rely more on sport science than sports trends*.

McNittgray, J. L. (1993). Kinetics of the lower-extremities during drop landings from 3 heights. *Journal of Biomechanics, 26*(9), 1037-1046.

Mero, A., & Komi, P. V. (1986). Force-velocity, EMG-velocity, and elasticity-velocity relationships at submaximal, maximal and supramaximal running speeds in sprinters. *European Journal of Applied Physiology and Occupational Physiology, 55*(5), 553-561.

Mero, A., & Komi, P. V. (1994). EMG, force, and power analysis of sprint-specific strength exercises. *Journal of Applied Biomechanics*, *10*(1), 1-13.

Mero, A., Komi, P. V., & Gregor, R. J. (1992). Biomechanics of sprint running - a review. *Sports Medicine, 13*(6), 376-392.

Miller, D. I. (1990). Ground reaction forces in distance running. In P. R. Cavagna (Ed.), *Biomechanics of distance running* (pp. 203-224). Champaign, IL: Human Kinetics.

Miller, D. I., & Nelson, R. C. (1973). *Biomechanics of sport: a research approach*. Philadelphia: Lea & Febiger.

Morin, J.-B., Bourdin, M., Edouard, P., Peyrot, N., Samozino, P., & Lacour, J. (2012). Mechnical determinants of 100-m sprint running performance. *European Journal of Applied Physiology*.

Morin, J. B., Edouard, P., & Samozino, P. (2011). Technical ability of force application as a determinant factor of sprint performance. *Medicine & Science in Sports & Exercise*, *43*(9), 1680-1688.

Morley, M. (2005). Myths and misconceptions on drills for closed skill development. *The Coach*(19), 26-40.

Morrissey, M. C., Harman, E. A., & Johnson, M. J. (1995). Resistance training models - specificity and effectiveness. *Medicine and Science in Sports and Exercise, 27*(5), 648-660.

Nagano, A., & Gerritsen, K. (2001). Effects of neuromuscular strength training on vertical jumping performance-a computer simulation study. *Journal of Applied Biomechanics, 17*(2), 113-128.

Nelson, W. (1985). Application of biomechical principles: optimisation of sport technique. In N. K. Butts, T. T. Gushiken & B. Zarins (Eds.), *The Elite Athlete*. Champaign, Illinois: Life Enhancement Publucations.

Nilsson, J., & Thorstensson, A. (1989). Ground reaction forces at different speeds of human walking and running. *Acta Physiologica Scandinavica, 136*(2), 217-227.

Nolan, L., Patritti, B. L., & Simpson, K. J. (2006). A biomechanical analysis of the long-jump technique of elite female amputee athletes. *Medicine and Science in Sports and Exercise, 38*(10), 1829-1835.

Novacheck, T. F. (1998). The biomechanics of running. *Gait & Posture, 7*(1), 77-95.

Nummela, A., Keranen, T., & Mikkelsson, L. (2007). Factors related to top running speed and economy. *International Journal of Sports Medicine, 28*(8), 655-661.

Okanda, J., Harada, T., & Tsuchuie, H. (2005). *Effects of squat and power clean movement power on running performance in sprinting.* Paper presented at the National Strength and Conditioning Association.

Olbrecht, J., & Clarys, J. (1983). EMG of specific strength training exercises for the front crawl. In A. P. Hollander, P. A. Huijing & G. De Groot (Eds.), *Biomechanics and Medicine in Swimming* (pp. 136-141). Champaign, IL: Human Kinetics.

Paruzel-Dyja, M., Walaszczyk, A., & Iskra, J. (2006). Elite male and female sprinters' body build, stride length and stride frequency. *Studies in Physical Culture and Tourism, 13*(1), 33-37.

Payton, C., & Lauder, M. (1995). The influence of hand paddles on the kinematics of front crawl swimming. *Journal of Human Movement Studies, 28*(4), 175.

Phillips, E. J. (2011). *A multidisciplinary examination of fast bowling talent development in cricket.* (Doctor of Philosophy), Queensland University of Technology.

Pohl, M. B., Messenger, N., & Buckley, J. G. (2007). Forefoot, rearfoot and shank coupling: effect of variations in speed and mode of gait. *Gait & Posture, 25*(2), 295-302.

Putnam, C., & Kozey, J. (1989). Substantive issues in running. *Biomechanics of sport*, 1-33.

Rimmer, E., & Sleivert, G. (2000). Effects of a plyometrics intervention program on sprint performance. *Journal of Strength and Conditioning Research, 14*(3), 295-301.

Rutherford, O., & Jones, D. (1986). The role of learning and coordination in strength training. *European Journal of Applied Physiology and Occupational Physiology, 55*(1), 100-105.

Sale, D., & Macdougall, D. (1981). Specificity in strength training a review for the coach and athlete. *Canadian Journal of Applied Sport Sciences, 6*(2), 87-92.

Salo, A. I. T., Bezodis, I. N., Batterham, A. M., & Kerwin, D. G. (2011). Elite Sprinting: Are Athletes Individually Step-Frequency or Step-Length Reliant? *Medicine and Science in Sports and Exercise, 43*(6), 1055-1062.

Scholz, J. P. (1990). Dynamic pattern theory—some implications for therapeutics. *Physical Therapy, 70*(12), 827-843.

Seagrave, L., Mouchbahani, R., & O'Donnell, K. (2009). Neuro-biomechanics of maximum velocity sprinting. *New Studies in Athletics, 24*(1), 19-27.

Sheppard, J. M. (2003). Strength and conditioning exercise selection in speed development. *Strength & Conditioning Journal, 25*(4), 26-30.

Sides, D., & Wilson, C. (2012). Intra-limb coordinative adaptations in cycling. *Sports Biomechanics, 11*(1), 1-9.

Slawinski, J., Bonnefoy, A., Leveque, J. M., Ontanon, G., Riquet, A., Dumas, R., & Cheze, L. (2010). Kinematic and kinetic comparisons of elite and well-trained sprinters during sprint start. *Journal of Strength and Conditioning Research, 24*(4), 896-905.

Sleivert, G., & Taingahue, M. (2004). The relationship between maximal jump-squat power and sprint acceleration in athletes. *European Journal of Applied Physiology, 91*(1), 46-52.

Smith, D. J., Norris, S. R., & Hogg, J. M. (2002). Performance evaluation of swimmers - Scientific tools. *Sports Medicine, 32*(9), 539-554.

Stergiou, N., & Scott, M. M. (2005). Baseline measures are altered in biomechanical studies. *Journal of Biomechanics, 38*(1), 175-178.

Stokes, D. (1985). Drills for better sprint techniques. *Modern Coach and Athlete, 23*(3), 31-34.

Stone, M. H., Collins, D., Plisk, S., Haff, G., & Stone, M. E. (2000). Training principles: Evaluation of modes and methods of resistance training. *Strength & Conditioning Journal, 22*(3), 65.

Stone, M. H., Pierce, K. C., Sands, W. A., & Stone, M. E. (2006). Weightlifting: a brief overview. *Strength & Conditioning Journal, 28*(1), 50-66.

Swinton, P. A., Stewart, A., Agouris, I., Keogh, J. W., & Lloyd, R. (2011). A biomechanical analysis of straight and hexagonal barbell deadlifts using submaximal loads. *The Journal of Strength & Conditioning Research, 25*(7), 2000-2009.

Tamminen, K. A., Holt, N. L., & Neely, K. C. (2013). Exploring adversity and the potential for growth among elite female athletes. *Psychology of Sport and Exercise, 14*(1), 28-36.

Taniguchi, Y. (1997). Lateral specificity in resistance training: The effect of bilateral and unilateral training. *European Journal of Applied Physiology and Occupational Physiology, 75*(2), 144-150.

Thepaut-Mathieu, C., Van Hoecke, J., & Maton, B. (1988). Myoelectrical and mechanical changes linked to length specificity during isometric training. *Journal of Applied Physiology, 64*(4), 1500-1505.

Thomas, J. R., & Nelson, J. K. (1996). *Research methods on physical activity (3rd ed)*. Champaign, IL: Human Kinetics.

Trezise, J., Bartlett, R., & Bussey, M. (2011). Coordination variability changes with fatugue in sprinters. *International Journal of Sports Science & Coaching, 6*(3), 357-363.

Tricoli, V., Lamas, L., Carnevale, R., & Ugrinowitsch, C. (2005). Short-term effects on lower-body functional power development: Weightlifting vs. vertical jump training programs. *Journal of Strength and Conditioning Research, 19*(2), 433-437.

Türk-Noack, U. (1994). *Field trial of the LAVEG laser diode system for kinematic analysis in various kinds of sports.* Paper presented at the ISBS-Conference Proceedings Archive.

Vardaxis, V., & Hoshizaki, T. B. (1989). Power patterns of the leg during the recovery phase of the sprinting stride for advanced and intermediate sprinters. *International Journal of Sport Biomechanics, 5*(3), 332-349.

Vincent, W. J., & Weir, J. P. (2012). *Statistics in Kinesiology, 4E*. Champaign, IL: Human Kinetics

Vucetic, V., Matkovic, B. R., & Sentija, D. (2008). Morphological Differences of Elite Croatian Track-and-Field Athletes. *Collegium Antropologicum, 32*(3), 863-868.

Wank, V., Frick, U., & Schmidtbleicher, D. (1998). Comparative considerations of the movement patterns when running on the treadmill and on the track. *Leistungssport*, *28*, 48-53.

Weyand, P. G., Sternlight, D. B., Bellizzi, M. J., & Wright, S. (2000). Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *Journal of Applied Physiology, 89*(5), 1991-1999.

Wiemann, K., & Tidow, G. (1995). Relative activity of hip and knee extensors in sprinting-implications for training. *New Studies in Athletics*, *10*, 29-29.

Wild, J., Bezodis, N. E., Blagrove, R., & Bezodis, I. (2011). A biomechanical comparison of accelerative and maximum velocity sprinting: strength training considerations for the Strength and Conditioning Coach. *Professional Strength and Conditioning, 21*, 23-37.

Wilmore, J. H., & Costill, D. L. (1994). *Physiology of sport and exercise*: Human Kinetics Publishers.

Wilson, C., Simpson, S., & Hamill, J. (2009). Movement coordination patterns in triple jump training drills. *Journal of Sports Sciences, 27*(3), 277-282.

Wilson, G. J., Murphy, A. J., & Walshe, A. (1996). The specificity of strength training: The effect of posture. *European Journal of Applied Physiology and Occupational Physiology*, *73*(3-4), 346-352.

Wilson, G. J., Newton, R. U., Murphy, A. J., & Humphries, B. J. (1993). The optimal training load for the development of dynamic athletic performance. *Medicine and Science in Sports and Exercise, 25*(11), 1279-1286.

Winter, D. A. (1990). *Biomechanics and motor control of human movement*. New York: John Wiley & Sons.

Wood, G. A. (1982). Data smoothing and differentiation procedures in biomechanics. *Exercise and sport sciences reviews, 10*(1), 308-362.

Yeadon, M. R. (1990). The simulation of aerial movement III. The determination of the angular momentum of the human body. *Journal of Biomechanics, 23*(1), 75-84.

Yeadon, M. R., Challis, J. H., & Ng, R. (1994). Personalised segmental inertia parameters. *Journal of Biomechanics, 27*(6), 770-770.

Young, M. (2006). Maximal velocity sprint mechanics. Retrieved October 13, 2013, from http://www.elitetrack.com/articles/youngsprintmechanics.pdf

Young, W., Benton, D., Duthie, G., & Pryor, J. (2001a). Resistance training for short sprints and maximum-speed sprints. *Strength and Conditioning Journal, 23*(2), 7-13.

Young, W., McDowell, M., & Scarlett, B. (2001b). Specificity of sprint and agility training methods. *Journal of Strength and Conditioning Research, 15*(3), 315-319.

Young, W., McLean, B., & Ardagna, J. (1995). Relationship between strength qualities and sprinting performance. *Journal of Sports Medicine and Physical Fitness*, *35*(1), 13-19.

Zatsiorsky, V., & Seluyanov, V. (1983). The mass and inertia characteristics of the main segments of the human body. *Biomechanics VIII-B, 56*(2), 1152-1159.

Zatsiorsky, V. M., & Kraemer, W. J. (1995). *Science and practice of strength training*: Human Kinetics Champaign, IL.