# UNDERSTANDING BIOMECHANICAL DIFFERENCES IN TECHNIQUE BETWEEN PHASES OF A SPRINT

# HANS CHRISTIAN VON LIERES UND WILKAU A thesis submitted for the degree of Doctor of Philosophy Cardiff Metropolitan University December 2017

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#### Declaration

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Signed..... (Candidate) Date....

#### Abstract

# UNDERSTANDING BIOMECHANICAL DIFFERENCES IN TECHNIQUE BETWEEN PHASES OF A SPRINT

#### Hans C. von Lieres und Wilkau, Cardiff Metropolitan University, Cardiff

Sprinting requires the rapid development of velocity while technique changes across multiple steps. Research Themes (Phase analysis, Technique analysis and Induced acceleration analysis) were formulated to investigate and understand the biomechanical differences in technique between the initial acceleration, transition and maximal velocity phases of a sprint.

Theme 1 (Phase analysis) revealed relatively large changes in touchdown variables (e.g. centre of mass height, touchdown distances, shank angles) during the initial acceleration phase. This likely reflects an increasing need to generate larger vertical forces early during stance as a sprint progresses. At toe-off, smaller yet progressive changes in variables (e.g. trunk angles and centre of mass height) across the initial acceleration and transition phases reflect a constraint determining decreases in propulsive forces during a sprint. Theme 2 (Technique analysis) revealed a trend linking smaller horizontal foot velocities and touchdown distances with smaller braking impulses during the transition and maximal velocity phases. Furthermore, moderate to large increases in negative work by the ankle plantar flexors and knee extensors suggests an increased contribution to absorb forces at those joints and maintain the height of the centre of mass as a sprint progresses.

Finally, theme 3 (Induced acceleration analysis) revealed that the braking impulses relative to body mass (expressed in  $m \cdot s^{-1}$ ) due to the accelerations at contact point, which largely resulted from the foot being decelerated at touchdown, increased from -0.01 ± 0.01  $m \cdot s^{-1}$  to -0.08 ± 0.02  $m \cdot s^{-1}$  between steps three to 19 of a sprint. The ankle moment provided the largest contributions to centre of mass acceleration throughout stance with the changing orientation of the ground reaction force vector ultimately determined by the increasing foot, shank and trunk angles as the sprint progressed. This thesis developed the conceptual understanding of the technical differences between different phases of sprinting. It will contribute to the development and evaluation of sprinting technical models associated with different phases of the event and provide a greater understanding of key contributors to performance. As a sprint progresses, sprinters should emphasise the development of the leg mechanics during the terminal swing and early stance phases to ensure step-to-step changes in braking impulses are managed.

### Publications

#### **Conference Presentations:**

#### International conference abstracts

von Lieres und Wilkau, H., Irwin, G., Bezodis, N., Simpson, S., & Bezodis, I.N. (June, 2017). Contributions to braking impulse during initial acceleration, transition and maximal velocity in sprinting. In: Proceedings of the 35rd *International Conference on Biomechanics in Sports*. Cologne, Germany.

von Lieres und Wilkau, H., Irwin, G., Bezodis, N., Simpson, S., & Bezodis, I.N. (July, 2016). Support leg joint contributions to center of mass acceleration during three phases of maximal sprinting. In: M. Ae, Y. Enomoto, N. Fujii & H. Takagi (eds.). *Proceedings of the 34rd International Conference on Biomechanics in Sports*. Tsukuba, Japan, pp. 1097-1100.

von Lieres und Wilkau, H., Irwin, G., Simpson, S. Elias, M., & Bezodis, I.N. (June, 2015). A comparison of different methods for identifying transition steps in the acceleration phase of sprint running. In: F. Colloud, M. Domolain and T. Monnet (Eds.), *Proceedings of the 33rd International Conference on Biomechanics in Sports.* Poitiers, France, pp. 106 – 109.

#### National conference abstracts

von Lieres und Wilkau, H., Irwin, G., Bezodis, N., Simpson, S., & Bezodis, I.N. (April, 2017). Differences in contributions to braking impulse between phases of maximal sprinting. In: *1<sup>st</sup> Pan-Wales Postgraduate Conference*, Swansea, Wales.

von Lieres und Wilkau, H., Irwin, G., Bezodis, N., Simpson, & Bezodis, I.N. (2016). Influence of the foot model on the results of an induced acceleration analysis in maximal sprinting. In: *Program and Abstract Book of the 31st Annual British Association of Sport and Exercise Sciences Biomechanics Interest Group* (Ed. M. Robinson), Liverpool John Moores University, UK, 23.

von Lieres und Wilkau, H., Irwin, G., Simpson, & Bezodis, I.N. (April, 2015). A case study of changes in transition steps and performance measures in sprint acceleration. In: *Program and Abstract Book of the 30th Annual British Association of Sport and Exercise Sciences Biomechanics Interest Group* (Ed. C. Diss), University of Roehampton, UK, 32.

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$M(\theta)\ddot{\theta} = JM_{i} + V(\theta, \dot{\theta})_{i} + G(\theta)_{i} \dots$	.53
$M_{11}(\theta)\ddot{\theta}_1 + M_{12}(\theta)\ddot{\theta}_2 = JM_1 + V(\theta,\dot{\theta})_{11} + V(\theta,\dot{\theta})_{12} + G(\theta)_{11}$	.53
$M_{21}(\theta)\ddot{\theta}_{1} + M_{22}(\theta)\ddot{\theta}_{2} = JM_{2} + V(\theta,\dot{\theta})_{21} + V(\theta,\dot{\theta})_{22} + G(\theta)_{21} \dots$	.53
$ \begin{pmatrix} M_{11}(\theta) \ M_{12}(\theta) \\ M_{21}(\theta) \ M_{22}(\theta) \end{pmatrix} \begin{pmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{pmatrix} = \begin{pmatrix} \tau_1 \\ \tau_2 \end{pmatrix} + \begin{pmatrix} V(\theta, \dot{\theta})_{11} \\ V(\theta, \dot{\theta})_{21} \end{pmatrix} + \begin{pmatrix} G(\theta)_{11} \\ G(\theta)_{21} \end{pmatrix} \dots $	.53
$\ddot{\theta} = M^{-1}(\theta) \left[ JM_i + G(\theta)_i + V(\theta, \dot{\theta})_i \right].$	.53
$P_{i} = M_{i}(\theta)\ddot{\theta}_{i} \times \dot{\theta}_{i}$	.55

# Chapter 3:

 $y_i = 0.25 \ast x_{i-1} + 0.5 \ast x_i + 0.25 \ast x_{i+1}$  ; i = 2 to (N-1)......74

# Chapter 4:

$\sum F_i = m_i \times a_i$	105
$Fy_i = m_i \times ay_i - Fy_{i-1}$	105
$Fz_i = m_i \times az_i - m_i \times g - Fz_{i-1}$	105
$\sum M_i = I_i \times \alpha_i$	106
$M_{pi} = (Fz_i \times r_i py) + (Fy_i \times r_i pz) + (Fz_{i-1} \times r_i dy) + (Fy_{i-1} \times r_i dz) + (I_i \times r_i dz) + $	$( \alpha_i) - M_{di} $
	106
$JP_i = M_{pi} \cdot \omega_i \qquad \dots$	106
$W_{nj} = \int_{t2}^{t1} JP_i dt_{-}$	106

# Chapter 5:

$A \times x = c_{-}$	150
$F_i - F_{i+1} + m_i g = m_i a_i \dots$	150
$\vec{a}_{cmi} + (\ddot{\theta}_i \times \vec{r}_{pi}) - (\dot{\theta}_i^2 \times \vec{r}_{pi}) = \vec{a}_{cm(i+1)} + (\ddot{\theta}_{(i+1)} \times \vec{r}_{d(i+1)}) - (\dot{\theta}_{(i+1)}^2 \times \vec{r}_{d(i+1)}) \dots$	150
$(F_{di} \times r_{di}) - (F_{pi} \times r_{pi}) + M_{dj} - M_{pj} = I_i \times \ddot{\theta}_i  \dots$	150
$ac = a_{cm1} + \ddot{\theta}_1(r_{d1}) - \dot{\theta}_1^2(r_{d1})$	151
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# Appendix A:

$F_i - F_{i+1} + m_i g = m_i a_i \dots$	.255
$F_i - F_{i+1} - m_i a_i = -m_i g \dots$	.255
$\vec{a}_{ji} = \vec{a}_i + (\ddot{\theta}_i \times \vec{r}_{ji}) - (\dot{\theta}_i^2 \times \vec{r}_{ji})$	.256
$\vec{a}_{pi} = \vec{a}_{d(i+1)} \dots$	.256
$\vec{a}_{pi} + (\ddot{\theta}_i \times \vec{r}_{pi}) - (\dot{\theta}_i^2 \times \vec{r}_{pi}) = \vec{a}_{d(i+1)} + (\ddot{\theta}_{d(i+1)} \times \vec{r}_{d(i+1)}) - (\dot{\theta}_{d(i+1)}^2 \times \vec{r}_{d(i+1)}) \dots$	.256
$\vec{a}_{2i} - \vec{a}_{(i+1)} + (\ddot{\theta}_i \times \vec{r}_{pi}) - (\ddot{\theta}_{(i+1)} \times \vec{r}_{d(i+1)}) = -(\dot{\theta}_{(i+1)}^2 \times \vec{r}_{d(i+1)}) + (\dot{\theta}_i^2 \times \vec{r}_{pi}) \dots$	.256
$(F_{di} \times r_{di}) - (F_{pi} \times r_{pi}) + M_{di} - M_{pi} = I_i \times \ddot{\theta}_i$	.256
$-(F_{di} \times r_{di}) + (F_{pi} \times r_{pi}) - I_i \times \ddot{\theta}_i = -M_{di} + M_{pi}$	.256
$\vec{a}_{p1} = \vec{a}_{d0} = 0$	.257
$\vec{a}_1 + (\ddot{\theta}_1 \times \vec{r}_1) - (\dot{\theta}_1^2 \times \vec{r}_1) = 0.$	.257

# Nomenclature and definitions

Symbols used	d to represent variables in equations throughout the thesis
F	Force
а	Acceleration
g	Acceleration due to gravity
т	Mass
СМ	Centre of mass
$Fy_i$	Horizontal joint reaction force at the proximal endpoint of the ith
	segment
Fzi	Vertical joint reaction force at the proximal endpoint of the ith
	segment
$ay_i$	Horizontal acceleration of the i <sup>th</sup> segment
$az_i$	Vertical acceleration of the i <sup>th</sup> segment
$Fy_{i-1}$	Horizontal joint reaction force at the distal endpoint of the ith
	segment
$Fz_{i-1}$	Vertical joint reaction force at the distal endpoint of the i <sup>th</sup> segment
Μ	Moment
I <sub>i</sub>	Moment of inertia of the i <sup>th</sup> segment
$\alpha_i$	Angular acceleration of the i <sup>th</sup> segment
$M_{pi}$	Moment acting on the proximal endpoint of the i <sup>th</sup> segment
M <sub>di</sub>	Moment acting on the distal endpoint of the i <sup>th</sup> segment
$r_{pi}$	Position vector of CM of segment i relative to proximal joint
r <sub>di</sub>	Position vector of CM of segment i relative to distal joint
JP <sub>j</sub>	Joint power of the j <sup>th</sup> joint
$\omega_j$	Angular velocity of the j <sup>th</sup> joint
$W_{nj}$	Joint work of the n <sup>th</sup> power phase of joint j
J P <sub>j</sub>	Joint power of the i <sup>th</sup> joint
t1	Start of power phase
t2	End of power phase
Σ	Sum of
А	Matrix of equations of motions (also see Appendix A1)
Х	Vector of unknowns (also see Appendix A3)
С	Vector of known variables (also see Appendix A2)
$F_{pi}$	Force at joint (at proximal joint of segment i)

F <sub>di</sub>	Force at joint (at distal joint of segment i)
$m_i$	Mass of i <sup>th</sup> segment
a <sub>cmi</sub>	Acceleration of centre of mass of ith segment
a <sub>ct</sub>	Acceleration at the foot-floor contact point
$M_{pi}$	Joint moment (at proximal joint of segment i)
M <sub>di</sub>	Joint moment (at distal joint of segment i)
$\ddot{ heta}_i$	Angular acceleration of ith segment
$\dot{ heta}_i$	Angular velocity of ith segment
у	Anterior-posterior horizontal axis
Z	Vertical axis
Ν	Number of values in the sample

Definition of the power phases at each stance leg joint quantified using the inverse dynamics analysis

- MTP+ / A+ / H+
   The positive power phase of the MTP joint during stance.
   The (+) is representative of a positive power phase while
   the (-) represents a negative power phase. The same
   convention is used for the ankle (A) and hip (H) joints.
- Kf+/ Ke-/ Ke+/Kf-Four power phases were identified at the knee (K). The letter after the K denotes whether the moment is flexor (Kf) or extensor (Ke) dominant. The positive or negative sign denotes whether the joint moment is absorbing (-) or generating (+) energy.

Abbreviations used for terminology throughout the thesis

DLT	Direct linear transformation
2D	two-dimensional
m	Metres
s	Seconds
LED	Light emitting diode
C7	Seventh cervical vertebra
MTP	Metatarsal-phalangeal
СМ	Centre of mass
CM-h	Centre of mass height

T <sub>start</sub>	Step the defines the start of the transition phase
MV <sub>start</sub>	Step the defines the start of the maximal velocity phase
CT≤FT	The step when flight time equals or exceeds the contact time
$\theta_{shank}$	Shank angle
$ heta_{ ext{thigh}}$	Thigh angle
θtrunk	Trunk angle
TD	Touchdown
ТО	Toe-off
V <sub>max</sub>	Maximal running velocity
SV	Step velocity
SL	Step length
SF	Step frequency
GRF	Ground reaction force
CM angle	Angle between the vector connecting the CM to the contact
	point relative to the ground

Symbols used to abbreviate statistical terminology throughout the thesis

x	Mean
SD	Standard deviation
RMSD	Root mean squared difference
%	Percentage

# Definitions of key terms used throughout the thesis

Sprint	A track and field event contested over distances up to 400 m where the aim is to cover the desired distance in the shortest time possible.
Technique	A movement sequence used to execute a specific task. Technique is a collective term that includes both kinematic (posture) and kinetic (e.g. joint moments, joint power, joint work) aspects of movement.
Posture	A collective term used to describe the orientation of the segments that dictate the orientation of the athlete relative to the ground.
Performance	A measure of the success associated with executing a task.

Phase	A distinct period of a movement or task that describes a specific aspect of the task.
Acceleration phase	The first phase in the sprint events, which defines a period during which the horizontal velocity of sprinters increases.
Initial acceleration phase	The first phase of sprint acceleration characterised by a forward orientated posture and relatively large step-to-step increases in horizontal velocity.
Transition phase	The second phase of sprint acceleration characterised by a more inclined posture and small step-to-step increases in horizontal velocity compared to the initial acceleration phase.
Maximal velocity phase	The phase in a sprint when the sprinter has an upright posture and maintains their running velocity above 95% of their maximal velocity.
Step	An event lasting from the instant of touchdown of one foot to the subsequent touchdown on the contralateral foot.
Step velocity	The mean velocity of the centre of mass across a step.
Step frequency	The number of steps a sprinter takes per second.
Step length	Horizontal displacement of the centre of mass across a step.
Flight phase	The period of the step when the sprinter is in the air.
Ground contact phase	The period of the step when one foot is on the ground.
Touchdown Distance	The horizontal distance between the contact point and the CM at the instant of touchdown. For consistency throughout the thesis, the horizontal location of the MTP was used as the contact point.
Toe-off Distance	The horizontal distance between the contact point and the CM at the instant of toe-off. For consistency throughout the thesis, the horizontal location of the toe location was used as the contact point.
Segment angles	All segment angles are relative to the right forward horizontal.

Inclined	Refers to the angular deviation from the right forward horizontal.
Braking phase	The period of the ground contact phase when the sprinter is generating a negative anterior-posterior GRF.
Propulsive phase	The period of the ground contact phase when the sprinter is generating a positive anterior-posterior GRF.
Breakpoint	A sudden deviation in the progression of a variable over time.
Clockwise/anti-clockwise rotations	Throughout this Thesis the mention of clockwise and anti-clockwise rotations are always in references to the running motion viewed from left to right.
External Validity	Describes the applicability of the data to real-world settings.
Accuracy	Describes the degree to which a measure represents the true value.
Reliability	Describes the degree to which a measure is repeatable.
Objectivity	Describes the bias within a certain measure.
Empirical research	Generation of knowledge by means direct measurement or observation.

#### Chapter 1 – Introduction

#### 1.1. Research overview

The main aim of the sprint events is to cover a predefined distance in as short a time as possible, with hundredths of a second often being the difference between first and second place. Based on velocity-time profiles, the sprint events can be divided into a reaction, acceleration, maximal velocity and deceleration phase (Bartonietz & Güllich, 1992; Mero, Komi & Gregor, 1992; Delecluse, Van Coppenolle, Willems, Diels, Goris, Van Leemputte & Vuylsteke, 1995). While the maximal velocity sprinters achieve is important to the final time (Moravec, Ruzicka, Susanka, Dostal, Kodejs & Nosek, 1988; Fuchs & Lames, 1990; Maćkala, 2007), the acceleration phase ultimately determines the velocity that sprinters can achieve (Bartonietz & Güllich, 1992). Depending on the ability level of the sprinters, the maximal velocity is generally achieved between 30 to 60 m with elite sprinters achieving their maximal velocity further into the sprint (Moravec et al., 1988). However, the maximum velocity achieved is dependent on their ability to maximally accelerate during the sprinter's whole acceleration phase (Bartonietz & Güllich, 1992) with the length of the acceleration is dependent on the ability of the sprinter (Delecluse, 1997).

To facilitate a more in-depth analysis and understanding of the acceleration phase, which would allow for a more manageable approach to preparing sprinters for the event, previous literature has proposed the sub-division of the acceleration phase into two phases (Seagrave, 1991; Bartonietz & Güllich, 1992; Delecluse et al., 1995; Qing & Kruger, 1995; Coh, Tomažin & Štuhec, 2006; Nagahara, Matsubayashi, Matsuo & Zushi, 2014; Crick, 2013a). Using a factor analysis on multiple velocity-time curves, Delecluse et al. (1995) identified two phases within sprint acceleration. The first phase or initial acceleration phase was associated with a high acceleration over the first 10 m. The second phase or transition phase was related to the ability to achieve a high maximal velocity up to 36 m (Delecluse et al., 1995). While this structure could be generalised across all sprinters it does not provide information on technical changes that occur during the acceleration phase. With the acceleration phase characterised by continuous changes in kinematics, a more in-depth understanding of these changes and their influence on the sprinter's performance may by facilitated by a more sensitive method of identifying the different phases within the acceleration phase of maximal sprinting.

It has been suggested that sudden changes in in the step-to-step progression of segment orientations occur between specific consecutive steps (i.e. breakpoint steps) during the acceleration phase (Bosch & Klomp, 2005). These breakpoint steps could therefore be identified to sub-divide the acceleration (e.g. Nagahara, Matsubayashi et al., 2014). Nagahara, Matsubayashi et al. (2014) identified breakpoints in the step-to-step increases in the height of the centre of mass (CM-h) which allowed the authors to sub-divide the 50 m sprint trial into three phases. Other studies have defined phases within sprint acceleration by identifying specific events. These events, which were based on contact and flight times, include the step when decreases in contact times plateau (Qing & Krüger, 1995), or when flight times equal or exceed contact times (Coh et al., 2006). Furthermore, British Athletics coaching literature suggested that changes in step-to-step progressions of shank and trunk angles could be used to identify the start of the transition and maximal velocity phases respectively (Crick, 2013a). Although these different measures have been successfully implemented to identify abrupt changes in kinematics, it is unclear how the steps identified by different measures compare. In addition, the appropriateness of the measures used previously to identify the breakpoint steps are still unclear.

Throughout the acceleration phase in sprinting, step characteristics and kinematic variables change (Maćkala, 2007; Debaere, Jonkers & Delecluse, 2013; Nagahara, Naito, Morin & Zushi, 2014; Nagahara, Matsubayashi et al., 2014). Nagahara, Matsubayashi et al. (2014) identified two breakpoints during maximal 50 m accelerations and reported abrupt changes in kinematics as sprinters crossed these breakpoints. Although changes in upper body kinematics and velocity contributions across multiple steps throughout a 50 m sprint have previously been reported by Nagahara, Matsubayashi et al. (2014) it is still unclear how the how the kinematics of the stance leg change throughout the acceleration phase. As the segments of the leg play an important role in influencing CM variables (e.g. CM-h, touchdown and toe-off distances) knowledge of these changes will build on the study of Nagahara, Matsubayashi et al. (2014). This will increase understanding of variables that are more visually accessible and therefore could assist coaches and sport scientists to better interpret the technical changes that occur during maximal sprinting.

It is well known from Newton's second law of motion that forces determine motion (i.e.  $\Sigma F = m \times a$ ). Recent studies have shown that world class sprinters have a better

technical ability to direct their resultant ground reaction force (GRF) vector more horizontally throughout the acceleration phase compared to athletes with similar physical capabilities (Morin, Edouard & Samozino, 2011; Rabita, Dorel, Slawinski, Sàez-de-Villarreal, Couturier, Samozino & Morin, 2015). As sprinters accelerate from low to high velocities, performance is influenced by their ability to continue to produce a net horizontal propulsive force (Rabita et al., 2015) while producing sufficiently large vertical forces to provide an appropriate flight time to allow them to prepare for the next stance phase (Hunter et al., 2005). However, in light of the decreasing ground contact times as running velocities increase, there is an increasing demand to generate the larger vertical ground reaction forces required to maximise running velocities (Weyand et al., 2000). Since the GRFs ultimately determine the acceleration of the sprinter's CM, knowledge of changes in the horizontal and vertical components of the GRF between consecutive steps is important to understand the demands of sprinting.

Previous research has generally aimed to understand the causes of motion through a description of the joint kinetics of the sprint by focusing in on a specific step or phase of the sprint. These include the block phase (Mero, Kuitunen, Harland, Kyröläinen & Komi, 2006; Brazil, Exell, Wilson, Willwacher, Bezodis & Irwin, 2016), first contact (Charalambous, Irwin, Bezodis & Kerwin, 2012; Debaere, Delecluse, Aerenhouts, Hagman & Jonkers, 2013, Bezodis, Salo, & Trewartha 2014), second contact (Jacobs & van Ingen Schenau, 1992; Debaere, Delecluse et al., 2013), transition (Johnson & Buckley, 2001: ~14 m; Hunter et al., 2004c: ~16 m; Yu, Sun, Yang, Wang, Yin, Herzog and Liu, 2016: ~12 m) and maximal velocity phase (Bezodis et al., 2008; Yu et al., 2016). The few studies that have reported joint kinetic data across multiple steps indicated some important changes in the energy absorption and generation strategies (Ito, Saito, Fuchimoto & Kaneko, 1992; Braunstein, Goldmann, Albracht, Sanno, Willwacher, Heinrich and Brüggemann, 2013) and joint moments (Yu et al., 2016) at the ankle and knee. However, these multi-step studies have either only focused on joint powers or work (e.g. Ito et al., 1992; Braunstein et al., 2013), joint moments (Yu et al., 2016) or have only reported their results in abstract form (e.g. Ito et al., 1992; Braunstein et al., 2013). Since the kinematic changes associated with the acceleration phase in sprinting are likely driven by the work done at the joints, a detailed analysis of the changes in joint kinematics and joint moments and powers between initial acceleration, transition and maximal velocity phases will add to the understanding of technical changes during maximal sprinting. The GRFs and resulting motion of the sprinter are largely determined by the forces exerted by muscles at the joints of the stance leg. It can therefore be speculated that changes in external ground reaction forces result from changes in joint kinetics.

While knowledge of the changes in joint kinematic and kinetic aspects of technique in sprinting provide insights into the musculoskeletal demands, the multi-segment nature of the body makes it difficult to intuitively predict their specific influence on the acceleration of the sprinter. An induced acceleration analysis (IAA; Zajac, Neptune & Kautz, 2002) allows the quantification of the contributions to whole-body and segmental CM accelerations generated by different forces (e.g. joint moments) acting on a multi-articulated body (Robertson et al., 2013). Although previous studies have reported the contributions to CM accelerations, these were either in abstract form (e.g. Cabral, Kepple, Moniz-Pereira, João & Veloso, 2013; Debaere et al., 2015; Koike & Nagai, 2015) or reported on contributions during a single phase in sprinting (Debaere, Delecluse, Aerenhouts, Hagman & Jonkers, 2015). It is therefore still unclear whether these contributions change during a maximal sprint and, if so, how they change. Since CM accelerations are dependent on the orientation of the segments and the magnitudes of the joint moments (Hoff & Otten, 2005), changes in either of those variables will result in changes in CM acceleration. Knowledge of these specific changes in contributions to whole-body and segmental accelerations will increase understanding of how performance changes during a maximal sprint.

Based on the theory that optimal performance in the sprint events is based on the acceleration phase, which is characterised by changes in kinematics and GRFs, an overall research aim was generated to understand the changes associated with maximal sprinting. To address the aim of this thesis, a thematic approach was taken based on the aim and purpose of this thesis.

#### 1.2. Research aim and purpose

There is currently a limited understanding of the biomechanical changes that occur during the acceleration phase in sprinting. As such the aim of this thesis was to investigate and understand biomechanical differences in technique between the initial acceleration, transition and maximal velocity phases of a sprint. The overall purpose of this thesis was to increase the conceptual understanding of the biomechanical changes in technique as a sprint progresses, and help develop coaching knowledge of biomechanical differences between the initial acceleration, transition and maximal velocity phases. This will increase understanding of the acceleration phase and provide valuable insights which can be used by coaches and sport scientists to develop their conceptual understanding of the technical changes as a sprint progresses and help to develop and evaluate training drills which specifically develop different aspects of changing acceleration technique. To address the overall aim of the thesis, a thematic approach was used based on three key research themes that emerged from the literature. These included: phase analysis; technique analysis; and an Induced acceleration analysis (Figure 1.1).

#### 1.2.1. Development of Research Themes

**Theme 1: Phase analysis:** Phases in maximal sprinting have previously been described in scientific (e.g. Delecluse, 1995; Čoh et al., 2006; Debaere, Jonkers & Delecluse, 2013; Nagahara, Matsubayashi et al., 2014) and coaching literature (e.g. Seagrave, 1992; Crick, 2013a). However, these studies have either suggested or used different measures. Knowledge of the most appropriate measure to sub-divide the acceleration phase in sprinting is necessary. This informed the development of the first research question of Theme 1:

# Research question (i) - How comparable are the breakpoints separating the initial acceleration, transition and maximal velocity phases when identified using different measures?

The measure which was identified to appropriately detect the breakpoints during maximal sprinting was used to sub-divide the acceleration phase of the participants and allow the description of the initial acceleration, transition and maximal velocity phases. It is known from previous literature (e.g. Nagahara, Matsubayashi et al., 2014) that step characteristics and kinematic variables change during the whole acceleration phase in sprinting. However, it is still unclear whether step-to-step changes are characteristic of the different phases of sprint acceleration and how stance leg kinematics change during different phases in sprinting. Research question ii was therefore formulated:

# Research question (ii) - How do step-to-step changes of step characteristics and kinematics differ between the initial acceleration phase, transition phase and maximal velocity phase?

Through a phase analysis, the aim of Theme 1 was to investigate differences in step-to-step changes in step characteristics and kinematic variables between the initial acceleration, transition and maximal velocity phases. The overall purpose of was to increase knowledge of the initial acceleration, transition and maximal velocity phases and assist with the development of technical models for different phases of sprinting. This will improve understanding of how variables that are more easily accessible to coaches and sport scientists in applied settings change within the phases of sprint acceleration.

Since the kinematic changes identified in Theme 1 are caused by kinetics and therefore largely driven by the work done at the joints, a detailed analysis of the differences in joint kinematics and kinetics between steps in the initial acceleration, transition and maximal velocity phases will add to the understanding of the technical changes during maximal sprinting.

**Theme 2: Technique analysis:** Joint kinetics have been widely reported in sprinting, however the majority of studies focused on single steps within specific phases of the sprint (e.g. Mann & Sprague, 1980; Johnson & Buckley, 2001; Bezodis et al., 2008; Bezodis et al., 2014). Although some studies have investigated differences in joint kinetics across multiple steps (Ito et al., 1992; Braunstein et al., 2013; Yu et al., 2016), these have focused either on joint moments or joint powers and therefore only offer an incomplete picture of the changes in joint kinetics during maximal sprinting. Theme 2 builds on the insights gained from the results of Theme 1 by providing a deeper level of understanding associated with changes in technique during maximal sprinting. An inverse dynamics analysis was employed to investigate the changes in joint kinematics and kinetic between steps three, nine and 19 and address research question iii:

# Research question (iii) - How do the joint kinematics and kinetics change between the initial acceleration, transition and maximal velocity phases?

Through a technique analysis, the aim of Theme 2 was to investigate the changes in joint kinetics between the initial acceleration, transition and maximal velocity phases. The purpose was to provide a new understanding of the changes in musculoskeletal characteristics as a sprint progresses, which will add valuable novel information to the body of knowledge of maximal sprinting. Furthermore, the knowledge gained will assist with the appraisal of training drills and exercises against the specific needs of the acceleration phase they are aimed at developing.

World-class sprinters are better able to maintain a relatively large ratio of anterior-posterior to resultant force compared to sub-elite sprinters (Morin et al., 2011; Rabita et al., 2015). While the results of Themes 1 and 2 could offer some new insights into maximal sprinting through the initial acceleration, transition and maximal velocity phases, it is still unclear how these kinematic and kinetic changes influence the changes in the acceleration of the CM.

Theme 3: Induced acceleration analysis: The contributions to CM acceleration are dependent on both the magnitude of the forces acting on the multi-segment system and the orientation of the segments (Hof & Otten, 2005). Theme 3 will build on the novel insights gained from Themes 1 and 2 by investigating how the kinematic and kinetic changes between the initial acceleration, transition and maximal velocity phases influence the contributions to vertical and horizontal CM acceleration quantified via an IAA (Zajac et al., 2002) and therefore address research question iv:

# Research question iv – What are the primary contributors to the acceleration of the CM during the initial acceleration, transition and maximal velocity phases?

The acceleration of the whole-body CM is influenced by the acceleration of individual segments. Therefore, knowledge of segmental induced accelerations would allow the identification of important interactions between different joint moments (Zajac, Neptune & Kautz, 2003) that are necessary for the execution of the ground contact phase in sprinting. The results of the IAA analysis allowed research question v to be addressed:

# Research question v - How do the segmental accelerations induced by the different joint moments change between the initial acceleration, transition and maximal velocity phases?

Using an Induced acceleration analysis, the aim of Theme 3 was to investigate the effects different forces (joint moments and non-muscular) acting on a sprinter have on the sagittal plane acceleration of the sprinter during steps from different phases of a sprint. The purpose was to build on the knowledge gained from Themes 1 and 2 and develop a greater depth of knowledge regarding the underlying mechanisms by which sprinters accelerate their CM during steps from different phases of a sprint. Furthermore, this knowledge can assist with the evaluation of the effect technical and physical changes may have on the performance of the sprinter.

Overall, three studies were designed to address the three themes and their respective research questions. This provided the basis to address the aim of this thesis.

#### 1.3. Organisation of Chapters

#### 1.3.1. Chapter 2: Review of literature

In Chapter 2, a review of the relevant sprinting literature is presented. This includes literature regarding phases within maximal sprinting, kinematic and kinetics during various steps and phases of sprinting and theoretical methods previously used in sprinting research. Selected literature concerned with relevant methodological approaches used in biomechanical analysis are also discussed.

#### 1.3.2 Chapter 3: Phase analysis: Phases in maximal sprinting

Theme 1 of this thesis, focusing on an increased understanding of the differences between the initial acceleration, transition and maximal velocity phases, is addressed in Chapter 3. This includes a comparison of the different measures previously used to sub-divide the acceleration phase in sprinting. The most appropriate measure was identified and this was then applied to sub-divide the acceleration phase in order to identify the delimiting steps for the initial acceleration, transition and maximal velocity phases. This is followed by a description of the step characteristics and kinematic changes associated with those phases. The findings of this chapter also informed the selection of the steps which were investigated in more detail in Chapters 4 and 5.

# 1.3.3 Chapter 4: Technique analysis: Changing joint kinematics and kinetics between different phases in maximal sprinting

Theme 2, focusing on the changes in joint kinematic and kinetics between steps form the initial acceleration, transition and maximal velocity phases, is addressed in Chapter 4. An inverse dynamics analysis (Winter, 2009) was used to investigate the differing musculoskeletal demands between the initial acceleration, transition and maximal velocity phases.

# 1.3.4 Chapter 5: Induced acceleration analysis: Changes in contributions to performance between different phases in maximal sprinting

Theme 3, focusing on the contributions to performance, is addressed in Chapter 5. This chapter builds on the knowledge gained from Themes 1 and 2 by the changes in contributions to CM acceleration between the initial acceleration, transition and maximal velocity phase. This will be discussed in the context of the changes in kinematic and kinetic characteristics identified in Chapter 4 (Theme 2). Furthermore, the accelerations induced on different segments of the body were investigated. This revealed important interactions between the different joint moments that are necessary to transfer forces to the ground.

#### 1.3.5 Chapter 6: General discussion

The findings of the three themes and their corresponding research questions, which are addressed by the investigations outlined in Chapters 3 to 5 are discussed in Chapter 6. Additionally, the appropriateness of the methodology used in this thesis and the novel contributions to knowledge, including practical implications, will be discussed. Finally, potential future investigations will be suggested.
#### UNDERSTANDING BIOMECHANICAL DIFFERENCES IN TECHNIQUE BETWEEN PHASES OF A SPRINT

**Aim:** To investigate and understand biomechanical differences in technique between the initial acceleration, transition and maximal velocity phases of a sprint.

**Purpose:** To develop the conceptual understanding of the biomechanical changes in technique as a sprint progresses, and help develop coaching knowledge of biomechanical differences between the initial acceleration, transition and maximal velocity phases.



**Figure 1.1.** A diagram representing the framework of this thesis highlighting the aims, key themes and research questions of each chapter.

# Chapter 2 - Review of Literature

# 2.1 Introduction

Sprint events are one of the most popular events in athletics. The 'stade' was part of the ancient Olympics where the athletes sprinted over a distance of 192 m (IAAF, n.d.). The 100 m sprint has been part of the modern Olympics since 1896 (IAAF, n.d.) and the winner of this race is considered the fastest man or women in the world.

# 2.2 Description of Phases

Based on the velocity profile, the sprint can be divided into an acceleration phase, maximal velocity phase and deceleration phase (Volkov & Lapin 1979, Mero, Komi & Gregor, 1992, Delecluse, Van Copenolle, Willems, Diels, Goris, Van Leemputte and Vuylsteke, 1995; Seagrave, 1996; Jones, Bezodis & Thompson, 2009; Crick, 2013a). During the 100 m sprint event, the race time is strongly correlated with the maximal velocity achieved (Maćkala, 2007, Fuchs & Lames, 1990). However, the maximal velocity achieved is dependent on the preceding acceleration phase, since sprinters can only run a velocity to which they have previously accelerated.

During the acceleration phase, sprinters exhibit an initial low drive out of the blocks (Jones et al., 2009), where acceleration is achieved through extension of the knee and hip joints (Bezodis et al., 2014), to an upright running position (Jones et al., 2009) characterised by a cyclical action of the leg about the hip joint (Debaere, Jonkers & Delecluse, 2013). Due to the dynamic nature of the acceleration phase, the technique of the sprinter changes constantly. Depending on the length of the sprint (e.g. 60 m or 100 m) and ability level of the sprinter, the acceleration phase can last between 30-60 m (Mero et al., 1992; Crick, 2013a) with faster sprinters reaching their maximal velocity later in the race (Ae, Ito & Suzuki, 1992). Once changes in posture have plateaued, the British Athletics coaching literature suggests that sprinters have started their maximal velocity phase (Crick, 2013a). During the deceleration phase, sprinters try to minimise the slowing down due to fatigue by altering their step characteristics (Bezodis, Irwin, Kuntze & Kerwin, 2011). The deceleration phase has been shown to start anywhere from 50 m onwards (Gajer, Thépaut-Mathieu & Lehénaff, 1999).

Due to the relatively large technical changes that occur during the acceleration phase in sprinting, describing acceleration as a single phase may be too simplistic to facilitate a deeper understanding of the technical changes that occur during sprint acceleration. In the sprint coaching literature, Dick (1987) was one of the first to sub-divide the acceleration phase into smaller phases. He coined the term 'pick-up acceleration' to describe the link between early acceleration and maximal velocity (Schiffer, 2009). Since then scientific (Bartonietz & Güllich, 1992; Delecluse et al., 1997; Debaere, Jonkers & Delecluse, 2013; Nagahara, Matsubayashi et al., 2014) and coaching literature (Seagrave, 1996; Mann, 2007; Crick, 2013a) have sub-divided the acceleration phase of sprinting to better analyse the mechanics adopted by sprinters. However, there is ambiguity in the sprint literature on how to best sub-divide the acceleration phase, which makes it difficult to identify consistent technical patterns. In addition, various measures have previously been used to identify phases within sprint acceleration (Figure 2.1) and these are discussed next.

Based on an analysis of velocity curves from 171 physical education students, Delecluse et al. (1995) identified two phases associated with the acceleration phase of a 100 m sprint. The first phase is characterised by the sprinters' ability to perform a high acceleration over the first 10 m of the race. The second performance phase was characterised by the sprinters' ability to achieve high maximal running velocities between 10 and 36 metres. The instrumentation used in this study was unique and allowed velocity to be calculated for every 0.1 m of distance covered. The velocity patterns of the participants in this study were found to be similar to that of sprinters in higher performance levels although some adjustments of the duration of the two phases would have to be made for highly skilled sprinters (Delecluse, 1997). Similarly, Mann (2007) used velocity to identify sub-phases within sprint acceleration. The initial acceleration phase was defined as the block phase and the first two steps. Steps three until the sprinter reached 80% of maximal velocity was defined as the transition phase. According to Mann (2007), the transition phase should be completed by step 11. Following that, Mann (2007) split the maximum velocity phase into two sections: the velocity achievement phase during which the sprinters continues to accelerate from 80% to 100% of their maximum velocity and the velocity maintenance phase then lasts from 100% of maximal velocity until the end of the race.



 $\uparrow$ : increase ( $\uparrow\uparrow$  = specifies greater increase compared to  $\uparrow$ ); ↓: decrease; → (plateau); %: percentage of maximal velocity; CT: contact time; FT: flight time; SL: step length; SF: step frequency; CM-h: Centre of mass height;  $θ_{shank}$ : Shank angle;  $θ_{trunk}$ : Trunk angle

**Figure 2.1.** Measures previously used to sub-divide the acceleration phase in sprinting. The different colour arrows indicate the different phases identified. Above each arrow is the distance/step number and associated discriminating variable, which the phase is based on. The block phase was not included.

While the definitions of Delecluse et al. (1995) and Mann (2007) are able to sub-divide the acceleration phase of a sprint, they do not take into consideration the technical changes that occur during the acceleration phase as velocity could increase smoothly irrespective of the underlying technical changes. It has been suggested that "abrupt changes in body posture" (Bosch & Klomp, 2005, p. 172) occur between consecutive steps during the acceleration phase. These abrupt changes could be identified as breakpoint steps (i.e. where the step-to-step progression curve of a variable defines a sudden change) and have previously been reported using step-to-step changes in CM-h (Nagahara, Matsubayashi et al., 2014). Few studies have attempted to identify breakpoint steps during the acceleration phase based on step-to-step changes in either temporal (e.g. Qing & Krüger, 1995; Čoh et al., 2006: contact and flight times) or postural (e.g. Nagahara, Matsubayashi et al., 2014: CM-h) measures. Furthermore, the British Athletics coaching literature suggests that changes in the step-to-step progression of shank and trunk angles can be used to identify the phases (Crick, 2013a).

Two authors have previously used temporal variables to sub-divide the acceleration phase. Qing and Krüger (1995) identified two sections in sprint acceleration based on the identification of a breakpoint, which defines the step when the sprinters moved from the first acceleration phase to the second acceleration phase. This breakpoint was based on the step when contact times reached a plateau. In their study, this occurred between steps 9 - 11 or between 12 - 17.5 m. It is however unclear precisely how they defined the plateau in contact times. Nonetheless, Qing and Krüger (1995) reported that during their first phase of acceleration, contact times decreased rapidly, trunk angle increased step-to-step and no knee flexion was observed during ground contact in this phase. During the second part of the acceleration phase: ground contact time and trunk angle remained stable. Čoh et al. (2006) identified a similar step. In their study, step 9 was identified as the breakpoint step between the initial acceleration phase and transition phase. Here, the breakpoint step was defined as the step where contact time became shorter than the flight time. The results of Coh et al. (2006) are however based on one athlete, and it is unclear how this applies to different athletes.

With the aim to confirm kinematic changes during the acceleration phase of sprinting, Nagahara, Matsubayashi et al. (2014) identified two breakpoints in the step-to-step change of the average CM-h during ground contact. The first transition step occurred between steps 3 and 6 while the second transition step occurred between steps 10 to 20. Based upon this premise, the whole sprint acceleration phase was separated into three sections. The first section was characterised by a high rate of acceleration, rapid increase in step frequency, rapid decrease in contact times and no knee flexion during ground contact. During the middle section of acceleration, step frequency stabilised, step length continued to increase and knee flexion was visible during stance. Nagahara, Matsubayashi et al. (2014) found that after the first transition step, trunk angles were still increasing. The third acceleration sector identified by Nagahara, Matsubayashi et al. (2014) which could coincide with the second acceleration phase identified by Qing and Krüger (1995) was characterised by a plateau in the step-to-step changes in contact times and trunk angles.

The British Athletics coaching literature has previously proposed that the initial acceleration phase ends when the shank is vertical at touchdown (Crick, 2013e) and the transition phase ends when the trunk angle at touchdown is vertical (Crick, 2013f). For well-trained sprinters, the initial acceleration phase is proposed to end after five to seven steps by which time sprinters will have reached around 80% of their maximal velocity (Crick, 2013e). The transition phase ends at approximately step 17 at which point sprinters will have reached around 95% of their maximal velocity (Crick, 2013f). These phase identifications are based on the idea that the there is a trade-off between anterior-posterior and vertical force production. The less inclined shank and trunk during the initial acceleration phase facilitate propulsive force production. During the transition phase, the vertical shank at touchdown is suggested to facilitate vertical force production while the less inclined trunk allows sprinters to retain some anterior-posterior force component during the latter half of stance (Crick, 2013e). While an 'upright' posture during the maximal velocity phase, emphasises vertical force production allowing sprinters to maximise running velocities (Crick, 2013f).

There is evidence of similarities regarding the structure of the acceleration phase (Figure 2.1) although the specific length of each phase differs between the studies. Data by Nagahara, Matsubayashi et al. (2014) shows the individual nature of the acceleration phase. Here the sprinters demonstrated the same phase structure while the lengths of each phase varied. The inconsistencies within the literature and individual response exhibited by sprinters makes it difficult to identify specific steps to sub-divide the acceleration phase in sprinting. A comparison of measures would facilitate the interpretation of coaching and scientific literature of this nature. Furthermore, the inconsistent naming of the phases within the acceleration phase of sprinting has the potential to cause some confusion, and makes it difficult to compare results from different sources of scientific and coaching information. An acceleration phase structure according to the British Athletics coaching literature (Crick, 2013a) will be adopted for this thesis (Figure 2.2).



**Figure 2.2.** Initial acceleration, transition and maximal velocity phases according to the British Athletics coaching literature (Crick, 2013a).

#### 2.2.1. Description of Phases summary

Traditionally the sprint has been sub-divided into three phases including an acceleration, maximal velocity and deceleration phase. However, to allow a better understanding of the technical changes that occur during the acceleration phase, studies have further sub-divided the acceleration phase into multiple phases. These sub-divisions have however been based upon different measures including distance, velocity and abrupt changes in step-to-step kinematic changes. By

identifying abrupt changes in kinematics (i.e. breakpoint steps), the delimiting steps of the initial acceleration, transition and maximal velocity phases can be determined (Nagahara, Matsubayashi et al., 2014). However, there is still much uncertainty regarding the appropriateness of the kinematic measures used in previous literature.

## 2.3 Sprint Technique

Following is a review of the technique associated with sprinting. While the sprint start must be considered an important factor contributing to the overall sprint (Jones et al., 2009), the remainder of this review and thesis will only consider the portion from block exit until maximal velocity.

## 2.3.1 Step Characteristics

## 2.3.1.1 Step Length and Step Frequency

Running velocity in sprinting is the product of step length and step frequency (Hay, 1994; Hunter, Marshall & McNair, 2004a) and the ratio between these vary between the phases in sprinting and between individuals (Dyson, 1962). During the acceleration phase, both step length and step frequency increase with increasing running velocity (Cronin & Hansen, 2006; Maćkala, 2007). However, while step frequency reaches a maximal value relatively quickly following block exit (Maćkala 2007; Debaere, Jonkers & Delecluse, 2013; Nagahara, Naito, Morin & Zushi, 2014; Rabita et al., 2015), step length continues to increase during the transition, maximal velocity and deceleration phases (Ae et al., 1992). During the deceleration phase, Bezodis et al., (2011) found that the fastest sprinters of the sample tended to increase step length while decreasing step frequency in an attempt to maintain their step velocity. The relationship between step length and step frequency has been described by many authors across an entire 100 m sprint (Salo et al., 2011), during the acceleration phase (Hunter et al., 2004a; Maćkala, 2007; Nagahara, Naito, Morin & Zushi, 2014; Debaere, Jonkers & Delecluse, 2013) and maximal velocity phase (e.g. Gajer et al., 1999; Kuitunen, Komi & Kyröläinen, 2002; Bezodis, 2006).

There are some conflicting views of the relative importance of step length and step frequency during the different phases of sprinting. Debaere, Jonkers & Delecluse (2013) reported that with a homogenous group of high-level Belgian sprinters, neither step length nor step frequency were found to be most influential to acceleration in the initial acceleration and transition phases in sprinting. On the other hand, when investigating the acceleration performance of participants ranging from physical education students to elite sprinters, Morin, Bourdin, Eduard, Peyrot, Samozino and Lacour (2012) reported that step frequency was significantly correlated to acceleration performance. During maximal velocity sprinting, previous studies have either identified step length (Gajer et al., 1999), step frequency (Kuitunen et al., 2002) or neither (Debaere, Jonkers & Delecluse, 2013) as the most influential variable on running velocity. Kuitunen et al. (2002) showed that when increasing velocity from 70% to 100%, step frequency was the dominant factor, while Gajer et al. (1999) found that once sprinters reach a certain level of proficiency, step length was more important to further improve performance. These conflicting results may be related to the level of participants in each study (e.g. Debaere et al., 2013; Morin et al., 2012), or the grouping of the sprinters used in the studies (Salo et al., 2011). Hunter et al. (2004a) also showed the influence of groupings on the outcome of the investigation. The authors reported that on a group level, step length was the determining variable while within individual differences showed step frequency was higher during faster trials. This suggests the importance for considering individual strategies during sprinting (Dufek, Bates, Stergiou & James, 1995).

Analysing the variation of step characteristics of elite male sprinters, Salo et al. (2011) found that in a group of elite sprinters, athletes achieved their performance via varying combinations of step length and step frequency. Furthermore, the authors identified the reliance of some sprinters on either step length or step frequency. This step characteristic reliance has since been suggested by other research (e.g. Naito, Kariyama, Miyashiro, Yamamoto & Tanigawa, 2013; Charalambous, Kerwin, Irwin, Bezodis & Hailes, 2011). Naito et al. (2013) analysed the type-specific characteristics between sprinters during the acceleration phase of sprinting. A cluster analysis was used to classify the participants as either step length or step frequency reliant based on the ratio of step length and step frequency during their maximal velocity phase (30-60 m). Although, 100 m performance did not differ between the groups, the authors reported that throughout the acceleration phase, step length reliant sprinters. Similarly, the step frequency reliant group

showed higher step frequencies throughout the sprint compared to the step length reliant sprinters. Furthermore, the authors reported that within the step length and step frequency reliant groups, the fastest sprinters within each of the groups showed a higher step length or step frequency respectively, after the seventh step. They concluded that the seventh step might represent an important breakpoint step in the acceleration phase. Although reliance on either step length or step frequency was previously found to be highly individual (Salo et al., 2011), the study by Naito et al. (2013) suggests that this reliance is visible throughout the sprint. The step characteristic reliance may have some important implications for training as Charalambous et al. (2011) reported that developing athletes showed the largest development of the step characteristic that they relied on when they started their training block.

Previous studies have generally attempted to associate absolute step length and frequency to sprinting performance. Recently, Nagahara et al. (2014a) studied the association between acceleration and rates of change in step length and step frequency in 21 male sprinters over 60 m. Nagahara et al. (2014a) found positive correlations between acceleration and rates of change in step frequency up to step two (r = 0.51-0.63). Between steps five to 19, acceleration was significantly correlated to rate of change in step length (r = 0.45-0.72). Contrary to Debaere, Jonkers & Delecluse (2013), who investigated the association between average step length and step frequency to acceleration during the initial acceleration and transition phase, Nagahara et al. (2014a) investigated the association between step-to-step changes in step characteristics and acceleration. This may have contributed to some of the different outcomes between the two studies. Nonetheless, Nagahara and his colleagues concluded that the acceleration phase could be divided into three phases based on the importance of step-to-step changes in either step frequency or step length to the acceleration of the sprinters.

A negative interaction has previously been described between step length and step frequency (Hunter et al., 2004a; Salo et al., 2011; Debaere, Jonkers & Delecluse, 2013; Nagahara, Naito, Morin & Zushi, 2014) where an increase in one variable could negatively influence the development of the other variable. This is believed to be due to the opposing mechanical requirements needed to develop each measure (Hunter et al., 2004a). It is therefore important to consider the development of the components of either step length or step frequency during the initial acceleration, transition and maximal velocity phases of sprinting.

# 2.3.1.2 Components of step length

Step length can be considered the sum of three separate components (Hay, 1994). These include the toe-off distance (the anterior-posterior distance between the contact point and CM at toe-off), the flight distance (the anterior-posterior distance the CM travel during flight) and touchdown distance (the anterior-posterior distance between the contact point and the CM at touchdown). Together, the touchdown distances and toe-off distances determine the contact length, which represents the distance that the sprinters' CM travels while in contact with the ground. The initial acceleration phase is characterised by a negative contact distance as the foot contacts the ground behind the CM (Mero et al., 1992; Nagahara, Matsubayashi et al., 2014). During this phase, both touchdown distance and contact length have been shown to increase relatively quickly compared to the transition phase (Nagahara, Matsubayashi et al., 2014). During the transition phase, touchdown distances continue to increase; however with smaller increments relative to the initial acceleration phase (Table 2.1) while contact lengths plateaued (Nagahara, Matsubayashi et al., 2014). During their maximal velocity phase, touchdown distances started to plateau (Nagahara, Matsubayashi et al., 2014). Mann (2007) reported that elite male and female sprinters tended to have a smaller touchdown distance during maximal velocity (0.195 - 0.201 m) compared to average sprinters (0.238 - 0.244 m).

Step Source		Touchdown distance [m]			
1	Mero et al., 1992	-0.13			
2	Mero et al., 1992	-0.04			
3	Mero et al., 1992	0.05			
16 m	Hunter et al., 2005	0.25			
15 m	Naito et al., 2015	0.20			
60 m	Ito, Fukada and Kijima, 2007	0.31			
Maximal velocity	Mann (2007)	0.195 -0.244			

Table 2.1. Change in touchdown distance throughout a sprint.

Less is known about the step-to-step changes of the toe-off distances. However this variable is influenced by the inclination of the body and it is therefore expected that toe-off distance decreases as the body becomes more upright (Hay, 1994). Flight

length, which during the maximal velocity phase contributes the largest portion to step length (Hay, 1994), is expected to increase during each step following block exit as CM height, running velocity and flight times increase (Hunter et al., 2004a). Hunter et al. (2005) reported that minimising touchdown distance (contacting the foot closer to the CM) leads to lower braking forces. As this variable increases during the acceleration phase, it could be speculated that better performance during the transition and maximal velocity phases could be achieved by minimising step-to-step increases in touchdown distances.

## 2.3.1.3 Components of step frequency

Step frequency, which is the inverse of the step time, is composed of flight time and contact time (Mann, 2007; Salo et al, 2011). Since step frequency reaches a plateau early on following the start (Salo et al., 2011; Debaere, Jonkers & Delecluse, 2013), total step time also does not change much during each step following the start (Mann, 2007; Salo, et al., 2011). However, the components that make up step time (i.e. flight and contact time; Figure 2.3) vary greatly during the sprint (Dyson, 1962; Mann, 2007; Čoh & Tomazin, 2006).



**Figure 2.3.** Contact (x) and flight times (•) during the initial acceleration, transition and maximal velocity phases from previous research in sprinting. Only studies that presented both flight and contact times were included.

Previous published data shows that during the initial steps following block exit, step times are dominated by contact times (Dyson, 1962; Salo, Keränen & Viitasalo, 2005; Mann, 2007; Čoh & Tomazin, 2006, Atwater, 1982). Čoh and Tomazin (2006) reported that during the first and second step, contact time comprised 77.4% and 65.8% of the total step time. Between the eighth to the tenth step, flight times equalled or exceeded contact times (Coh & Tomazin, 2006). These results were however based on a single sprinter and it is unclear how this relates to different sprinters across different performance levels. As sprinters continue to progress towards their maximal velocity, contact times decrease while flight times increase (Qing and Krüger, 1995; Coh & Tomazin, 2006; Debaere, Jonkers & Delecluse, 2013). Ballreich (1969) found that contact time decreased independent of sprinting ability in the first 12 to 15 steps after which contact times stabilised. During maximal velocity sprinting, contact times have plateaued (Atwater, 1982; Mero et al., 1992; Debaere, Jonkers & Delecluse, 2013, Kuitunen et al., 2002; Mann & Herman, 1985; Mann, 2007), but flight times continue to increase as step velocity increases (Nagahara, Matsubayashi et al., 2014).

Theoretically, maximising propulsive impulses while minimising contact time could be considered desirable (Charalambous, 2012). The longer contact times during the initial portion of the race could allow sprinters to take advantage of their strength capabilities (Mann, 2007) and produce a large propulsive impulse during ground contact. This would benefit the development of the sprinters' contact length, as a longer contact time would allow the sprinters' CM to travel further during ground contact. This is partly supported by Kugler and Janshen (2010), who reported that during the first step faster athletes exhibited a strategy involving a longer contact time. This allowed their CM more time to move farther forward relative to their contact point and therefore generate higher propulsive forces (Kugler & Janshen, 2010). Therefore, it might seem advantageous to maximise performance by increasing contact times and minimising flight times as this could allow a sprinter greater opportunity to accelerate during the initial acceleration phase. However, given the negative interaction between step length and step frequency (e.g. Debaere, Jonkers & Delecluse, 2013) and the influence of the step-to-step changes in step frequency on the acceleration of the sprinter over the first three steps (Nagahara et al, 2014a), the strategy of maximising performance by increasing contact times may be detrimental to performance across multiple steps.

Performance during the transition and maximal velocity phases and across the whole sprint was previously associated with lower ground contact times (Weyand et al., 2000; Morin et al., 2012; Debaere, Jonkers & Delecluse, 2013). Nagahara et al. (2014a) reported that the rate of decrease of contact times between steps 11 and 16 and the rate of increase in flight times between steps 8 to 10 were associated with larger acceleration performances. While the decreasing contact time influenced the contact length of the sprinter, the increasing flight times during the transition phase would benefit the continued increase in step length by increasing the flight length component of step length.

# 2.3.1.4 Summary of step characteristics

The step velocity of a sprinter is dependent on the step length and the step frequency. However, these two components of running velocity are negatively related due to the different mechanisms required to develop them (Hunter et al., 2004a). While step frequency increases relatively quickly over the first couple of steps (e.g. Debaere, Jonkers & Delecluse, 2013) and then plateaus during the transition and maximal velocity phases, step length has been shown to increase throughout the different phases of a sprint (Ae et al., 1992). These patterns can be better understood when investigating the changes in the components underlying step length (i.e. contact length and flight length) and step frequency (i.e. contact time and flight time).

#### 2.3.2 Segment and Joint kinematics

The orientation of the CM relative to the ground plays an important role in sprinting (di Prampero, Fusi, Sepulcri, Morin, Belli & Antonutto, 2005). Di Prampero et al. (2005) showed that the angle between the line connecting the ground contact point and the CM relative to the ground (CM\_angle) is dependent on the anterior-posterior and vertical acceleration of the sprinter. Furthermore, Kugler and Janshen (2010) reported that faster sprinters achieved superior acceleration performances by achieving a lower CM angle during stance (i.e. less inclined). Since the angle of the CM depends on the position of the different segments, changing segment

orientations therefore play an important role in influencing step-to-step changes in external ground reaction forces during sprinting.

During any running action, each leg cycles though a stance and a swing phase. The function of the swing phase is to reposition the limbs so that force can effectively be applied during the subsequent stance phase (Crick, 2013c). Although this thesis will focus mainly on the stance phase in sprinting, a short description of the swing phase is presented next. Regarding the mechanics of the swing phase, most of the literature exists within coaching texts and education resources. The swing phase can be sub-divided into a residual phase, recovery phase and the ground preparation phase (Crick, 2013c). The residual phase is defined as the time between toe-off and when the thigh begins to move forwards relative to the CM. The recovery phase starts when the thigh starts to move forward until maximum hip flexion is reached, while the ground preparation phase starts after maximum hip flexion is achieved and ends at touchdown (Crick, 2013c). The whole recovery action is initially characterised by a low repositioning of the leg (measured by the height of the foot relative to the ground) during the initial acceleration phase. Throughout the acceleration phase, the foot and thigh are gradually recovered higher (increase foot ground distances and smaller hip flexion angles and the end of the recovery phase) with each successive step (Crick, 2013e). The majority of previous research tended to agree that during the maximal velocity phase, faster sprinters exhibited increased knee flexion as the swing leg thigh passed the midline of the body during recovery (Mann & Herman, 1985; Mann, 2007; Ito et al., 2007). Furthermore, sprinters generally achieve a higher knee elevation at the end of the recovery phase (Mann, 2007; Crick, 2013c). This is thought to aid the sprinter in accelerating the foot down and backwards relative to the CM during the ground preparation phase (Mann, 2007; Crick, 2013c). A high knee lift at the end of the recovery phase is however not a precursor to a fast swing back velocity of the leg relative to the CM prior to ground contact. Ae et al. (1992) reported that two elite sprinters achieved a similar swing back velocity although one achieved a knee lift comparable to those of university level sprinters.

During the ground preparation phase, previous studies show that faster sprinters are able to sufficiently minimise the forward velocity of the foot prior to touchdown (i.e. generate a larger negative forward foot velocity relative to the CM) (Mann & Herman, 1985; Ae, Ito & Suzuki, 1992; Hunter et al., 2005; Mann, 2007). Further, well-trained sprinters are able to better accelerate the foot down into the ground at higher velocities (Clark, Laurence, Ryan & Weyand, 2014). The anterior-posterior and vertical foot velocity prior to touchdown have previously been linked to braking (Hay, 1994; Hunter, Marshall & McNair, 2005) and vertical (Clark et al., 2014a) force production following touchdown. This will be discussed in more detail within section 2.3.3.

Throughout the initial acceleration, transition and maximal velocity phases, large changes in kinematics have previously been observed (Table 2.2). These changes are characterised by sprinters gradually becoming upright and contacting the ground further ahead of their CM (Mann, 2007; Debaere, Jonkers & Delecluse, 2013; Nagahara, Matsubayashi et al., 2014; Crick, 2013a). During the initial acceleration phase, relatively large increases in CM velocity occur with each touchdown compared to the transition and maximal velocity phases (Delecluse et al., 1995). As sprinters approach the end of initial acceleration phase, they will have reached about 80% of their maximal velocity (Crick, 2013e) and by the end of the transition phase, the sprinters should have reached 95% of their maximal velocity (Crick, 2013f). The relatively large step-to-step increase in velocity during the initial acceleration phase is aided by the less inclined posture resulting in a smaller CM angle. Theoretically, this would therefore require larger forward acceleration of the CM to maintain postural equilibrium (di Prampero et al., 2005).

The position of the CM relative to the foot is determined by the orientations of the segments of the limbs and the trunk. The British Athletics coaching literature suggests that during the initial acceleration phase, the shank exhibits angles less than 90° at touchdown (Crick, 2013a) and increases between 6 to 8° per step (Crick, 2013e). While Crick (2013e) suggests that the smaller shank and CM angles during the initial acceleration phase are important to generate large propulsive forces, large step-to-step increases step-to-step increases in shank angles may reflect and increasing need to generate larger vertical forces and facilitate increases in flight times (Crick, 2013e). However, large step-to-step increases (i.e. >8° per step) in

shank angles could result in large increases in touchdown distances, which have previously been linked to larger braking forces (Hunter et al., 2005).

Kinematic variables	Initial Acceleration	Transition	Maximum Velocity
Velocity	< 75-80% of V <sub>max</sub> (Crick, 2013e)	<95% of V <sub>max</sub> (Crick, 2013e)	>95 of V <sub>max</sub> (Crick, 2013e)
CM-h	Rapid change (Nagahara, Matsubayashi et al., 2014)	Moderate change (Nagahara, Matsubayashi et al., 2014)	No change (Nagahara, Matsubayashi et al., 2014)
Trunk angle (°) -relative to horizontal	<upright (Crick, 2013f; Nagahara, Matsubayashi et al., 2014)</upright 	<upright (Crick, 2013f; Nagahara, Matsubayashi et al., 2014)</upright 	Upright (Crick, 2013f; Nagahara, Matsubayashi et al., 2014)
Thigh angle (°) -relative to horizontal	TD: 150° -159.2- (Cronin & Hansen, 2006)	) <sup>-</sup>	TD: 150°-159.2- (Cronin & Hansen, 2006)
Shank angle (°) -relative to horizontal	TD: <90° (Crick, 2013f)	TD: ~90° (Crick, 2013f)	TD: ~90° (Crick, 2013f)
Hip angle (°)	TD: 99 TO: 172° (Jacobs & von Ingen Schenau, 1992)		TO: 167-170° (Mann, 2007; Mann & Herman, 1985)
Knee angle (°)	TD: 111° (2 <sup>nd</sup> contact) (Jacobs & von Ingen Schenau, 1992)	TD: 145-150° (Cronin & Hansen, 2006)	TD: 167-165° (Cronin & Hansen, 2006)
	TO: 160° (Jacobs & von Ingen Schenau, 1992)		TO: 157° (Mann, 2007; Mann & Herman, 1985)
Hip ROM (min to max)	Increasing (Nagahara, Matsubayashi et al., 2014)	Plateaus around step 8 (Nagahara, Matsubayashi et al., 2014)	-
Contact knee extension angular velocity (º/s)	Increasing (Nagahara, Matsubayashi et al., 2014)	Plateaus around step 8 (Nagahara, Matsubayashi et al., 2014)	-
Touch-down distance	~ -0.13 – 0.05 m (Mero et al., 1992)	~ 0.20 m (Naito et al., 2015) ~ 0.25 m (Hunter et al., 2004b)	~ 0.31m (Ito et al., 2007)
Toe-off distance		~ 0.66 - 0.69 (Naito et al., 2015)	

**Table 2.2.** Kinematic characteristics during the stance phases of the initial acceleration, transition and maximum Velocity Phases.

 CM: centre of mass; CM-h: vertical position of the CM; ∆: change; TD: touchdown; TO: toe-off; The data was assigned to the different phases based either on the suggestions by the authors or the location of the sprint where the data was collected.

The British Athletics coaching literature also suggests that during the initial acceleration phase that the trunk angle should increase at the rate 25% to 50%,

slower than that of the shank angle (Crick, 2013e), so that the trunk angle of 45° to 55° degrees by the end of the initial acceleration phase (Crick, 2013e). The step-to-step changes in the orientations of the segments of the stance leg at touchdown and toe-off during the initial acceleration, transition and maximal velocity phases within a group of sprinters have however not yet been quantified.

The initial acceleration phase is also characterised by relatively large step-to-step increases in vertical position of the CM-h compared to the transition phase (Nagahara, Matsubayashi et al., 2014). This increase during the initial acceleration phase can be attributed to increases in hip height as stance limb mechanics change (Nagahara, Matsubayashi et al., 2014). Further increases in CM-h during the transition phase are attributed to continued step-to-step increases in trunk and head angles (Nagahara, Matsubayashi et al., 2014). Once an upright posture is reached, which is characteristic of the maximal velocity phase (Crick, 2013f; Nagahara, Matsubayashi et al., 2014), changes in CM-h, trunk angle and head angle plateau.

Apart from influencing the position of the CM, the orientation of the segments play an important role in their potential to contribute to the anterior-posterior velocity of the CM. The contribution of the rotational kinematics of segments to linear velocity of the CM are governed by geometrical constraints (van Ingen Schenau, Bobbert & Rozendal, 1987; Bobbert & van Ingen Schenau, 1988). The contribution of a segments angular motion to the translation of the CM depends on the segments angular velocity and orientation (Jacobs & van Ingen Schenau, 1992). The proximal to distal sequencing would ensure that maximum joint angular velocities are reached as their respective segments approach a vertical orientation, therefore maximising the contribution to the anterior-posterior translation of the CM (Jacobs & von Ingen Schenau, 1992).

Based the geometric constraint theory (van Ingen Schenau et al., 1987), Nagahara, Matsubayashi et al. (2014) calculated the contributions to CM velocity by the relative anterior-posterior velocity of the segments. The relative anterior-posterior segment velocity was calculated by subtracting the distal anterior-posterior velocity of the foot, shank and thigh from the proximal anterior-posterior velocity of the respective segment. The authors reported that, step-to-step increases in the relative anteriorposterior velocity of the thigh and shank contributed to the relatively large increases in CM velocity associated with the initial acceleration phase (Nagahara, Matsubayashi et al., 2014). Throughout the transition phase, step-to-step increases in CM velocity were supported by the step-to-step increases in the relative anteriorposterior velocity of the thigh, shank and foot (Nagahara, Matsubayashi et al., 2014). During the maximal velocity phase, further increases in the relative anteriorposterior velocity of the foot and shank contributed to the relatively small increases in CM velocity (Nagahara, Matsubayashi et al., 2014). Nagahara, Matsubayashi et al. (2014) concluded that these results suggest a change in acceleration strategy throughout the acceleration phase in sprinting.

During all stance phases in sprinting, consistent ankle and hip joint kinematic patterns have been observed (Jacobs & van Ingen Schenau, 1992; Charalambous et al., 2012; Bezodis, Salo & Trewartha, 2014; Nagahara, Matsubayashi et al., 2014). At the knee joint, an extension pattern was exhibited throughout stance during the initial acceleration phase (Charalambous et al., 2012; Bezodis et al., 2014; Nagahara, Matsubayashi et al., 2014). This changed to a flexion-extension pattern during the transition and maximal velocity phases (Hunter et al., 2004c; Johnson & Buckley, 2001; Bezodis et al., 2008; Nagahara, Matsubayashi et al., 2014). The flexion to extension pattern at the knee has recently been shown to occur from step four onwards (Nagahara, Matsubayashi et al., 2014).

Regarding joint angular velocities, a proximal to distal sequencing of the lower limb joint angular velocities has generally been reported throughout the sprint (Johnson & Buckley, 2001; Hunter et al., 2004c; Bezodis et al., 2008; Charalambous et al., 2012) where peak extension angular velocity is reached by the hip first followed by the knee and finally the ankle joint. Ae et al. (1992) and Ito, Fukuda and Kijima (2007) found that faster sprinters displayed higher hip extension velocities (r=0.284, p<0.05, Ito et al., 2007). Mann and Herman (1985) reported a similar trend in hip extension velocities during the final of the 200 m of the 1984 Summer Olympics. They reported that the gold and silver medallist displayed higher hip extension velocities, Ito et al. (2007) reported that faster sprinters than the 8th place finisher. Regarding knee extension velocities, Ito et al. (2007) reported that faster sprinters (r=-0.407, p<0.1) while some even exhibited a knee

flexor angular velocity throughout stance. Ito et al. (2007) suggested that if the knee remains fixed during stance, 100% of the hip extension could be converted to a clockwise rotation of the leg. However, if the knee flexes during stance (as the case with some elite sprinters) the velocity transferred down the leg could exceed the velocity created by the hip extension alone. In this case, the clockwise angular velocity of the thigh generated by the hip musculature and the clockwise angular velocity of the shank will result in an increased clockwise rotation of the whole leg.

# 2.3.2.1 Summary of segment and joint kinematics

The orientation of the segments not only dictate the CM angle which is mathematically linked to CM acceleration (di Prampero, 2005), but also influence the conversion of angular segmental motion to the translation of the CM (van Ingen Schenau et al., 1987). Due to the dynamic nature of the acceleration phase in sprinting, relatively large changes in segment orientation can be expected to occur. Although studies exist describing kinematic changes (e.g. Nagahara, Matsubayashi et al., 2014) across multiple steps within the acceleration phase, a detailed description of the step-to-step changes in segment orientations (especially of the stance leg) is still lacking. This would complement the work of Nagahara, Matsubayashi et al. (2014) and provide coaches and applied scientists a better understanding of how variables that are more visually accessible change during the initial acceleration, transition and maximal velocity phases.

# 2.3.3 External Kinetics

Hunter et al. (2005) suggested that for analysis purposes, the GRF can be broken down into its three orthogonal components (vertical, anterior-posterior and medio-lateral). The anterior-posterior component has been further sub-divided into braking and a propulsive force. During the braking phase, the body's CM velocity decreases due to the negative anterior-posterior ground reaction force applied to the sprinter's foot by the ground (Hay, 1994). The velocity of the CM then increases again during the subsequent propulsive phase. Although many studies have reported ground reaction forces in sprinting, these have generally focused on single or multiple steps from the initial acceleration phase, transition phase or maximal velocity phase (Table 2.3). This makes it difficult to identify changes between steps from different phases in maximal sprinting. Few studies have reported multiple steps from different phases. Yu, Sun, Chen Yang, Wang, Yin, Herzog and Liu (2016) reported external kinetics from one step from the transition and maximal velocity phases. Rabita et al. (2015) investigated the determinants of maximal sprinting acceleration over multiple steps of a 40 m 'virtual' sprint. Furthermore, a recent pilot study was publish in abstract form that detailed external kinetics over 25 successive steps (Nagahara, Mizutani & Matsuo, 2016).

From the literature, the braking phase as a proportion of the whole contact changes increased as the sprint progressed. During the initial acceleration phase previous studies reported braking phases lasting 6 -13% of ground contact (Mero et al., 1992; Salo et al., 2005). This increased to 32% during the transition phase (Yu et al., 2016) and 40 - 48% during maximal velocity (Mero & Komi, 1988; Bezodis, 2006; Yu et al., 2016). The peak braking forces expressed in body weights also increased from the initial acceleration phase (~ -0.06 to -0.71 BW; Mero 1987; Bezodis et al., 2014) to the transition (~ -0.67 ± 0.25 BW; Yu et al., 2016) and maximal velocity phases (~ -0.91 to -1.30 BW; Bezodis, 2006; Yu et al., 2016).

When comparing propulsive forces reported in previous literature, it appears that peak forces decrease from the initial acceleration, transition and maximal velocity phase (Table 2.3). During the first step, propulsive forces were previously measured at 1.04 -1.31 BW (Bezodis et al., 2014). By the time sprinters reached their maximal velocity, propulsive forces decreased to 0.68 - 0.91 BW (Bezodis, 2006). Interestingly, Yu et al. (2016) found no significant (p=0.063) differences between the peak forces generated during a step from the transition (0.90 ± 0.11 BW) and maximal velocity (0.88 ± 0.13 BW) phases.

Kinetics	Initial Acceleration	Transition	Maximum Velocity
Braking phase	<b>Duration:</b> ~11% (Mero, 1988)	Duration:	<b>Duration:</b> ~43 - 44% (Mero et al., 1987)
			~40 – 48% (Bezodis, 2006)
		32 ± 8% (Yu et al., 2016)	43 ± 3% (Yu et al., 2016)
	<b>Peak force:</b> -0.6 BW (Mero, 1988)	Peak force:	<i>Peak force:</i> -0.9 to -1.3 BW (Bezodis, 2006)
	-0.1 to - 1.2 BW (Bezodis et al., 2014)	-0.7 ± 0.3 BW (Yu et al., 2016)	-1.3 ± 0.2 BW (Yu et al., 2016)
	∆ <b>velocity<i>:</i></b> -0.04 m⋅s <sup>-1</sup> (Mero, 1988)	∆ <b>velocity<i>:</i></b> -0.10 m⋅s <sup>-1</sup> (Hunter et al, 2005)	$\Delta$ velocity:
	-0.02-0.06 m⋅s <sup>-1</sup> (Salo et al., 2005)	-0.09 m⋅s <sup>-1</sup> (Yu et al., 2016)	-0.19 m⋅s <sup>-1</sup> (Yu et al., 2016)
Propulsion phase	<b>Duration:</b> ~ 89% (Mero et al., 1987)	Duration:	<b>Duration:</b> 56 – 57 % (Mero et al., 1987)
			52 - 60% (Bezodis, 2006)
		68 ± 8 % (Yu et al., 2016)	57  ± 3% (Yu et al., 2016)
	<b>Peak forces:</b> 1.0 -1.3 BW (Bezodis et al., 2014)	Peak forces:	<b>Peak forces:</b> 0.42 BW (Mero et al., 1992)
			0.68 – 0.91 BW (Bezodis, 2006)
		0.90 ± 0.11BW (Yu et al., 2016)	0.88 ± 0.13 BW (Yu et al., 2016)
	∆ <b>velocity:</b> 1.16-0.56m⋅s <sup>-1</sup> (Salo et al., 2005)	∆ <b>velocity:</b> 0.25 m⋅s <sup>-1</sup> (Hunter et al., 2005)	$\Delta$ velocity:
		0.41 m⋅s <sup>-1</sup> (Yu et al., 2016)	0.29 m⋅s <sup>-1</sup> (Yu et al., 2016)
Vertical	<b>Peak force:</b> 1.1 BW (Mero, 1988)	Peak force:	<b>Peak force:</b> 3.6 – 4.4 BW (Bezodis, 2006)
	1.9 -2.3 BW (Bezodis et al., 2014)	3.3 ± 0.5 BW (Yu et al., 2016)	4.0 ± 0.5 BW (Yu et al., 2016)
	-	∆ <b>velocity:</b> 0.99 m⋅s <sup>.1</sup> (Hunter et al., 2005)	∆ <b>velocity:</b> 1.11 - 1.27 m⋅s <sup>-1</sup> (Bezodis, 2006)

Table 2.3. External kinetics during initial acceleration, transition and maximal velocity.

-  $\Delta$ : change in; The data in this table was taken from various sources. When not presented in the format used in this thesis the values were adjusted based on the participants mass. The Yu et al. (2016) data is the only direct comparison between phases from the same study.

The sum of the impulses (force  $\times$  time) created by these braking and propulsive forces determine the change in velocity of the CM. In the first four steps of a sprint, Salo et al (2005) reported that net anterior-posterior impulses decreased from about 92 Ns (or a 1.16 m·s<sup>-1</sup> increase in velocity) to 44 Ns (0.56 m·s<sup>-1</sup>) between step one and four. Around the 14 m mark, Johnson and Buckley (2001) reported a net anterior-posterior impulse of 19.5 Ns (0.28 m·s<sup>-1</sup>) while Hunter et al. (2005) reported that net anterior-posterior impulse was about 18 Ns (0.25  $m \cdot s^{-1}$ ) 16 m from the start. During the maximal velocity phase, the net anterior-posterior impulse was previously reported as 3.9 to 10.8 Ns or 0.06 to 0.13 m·s<sup>-1</sup> (Bezodis, 2006). Morin, Slawinski, Dorel, de Villareal, Courtier, Samozino, Brughelli and Rabita, (2015) reported that the mean anterior-posterior impulse between 0 to 20 m was  $64.1 \pm 9.03$  Ns (0.805)  $\pm$  0.061 m·s<sup>-1</sup>). Between 20 to 40 m, the mean anterior-posterior impulse decreased to 10.6  $\pm$  2.9 Ns (0.132  $\pm$  0.030 m·s<sup>-1</sup>) (Morin et al., 2015). Nagahara et al., (2016) showed that while decreasing propulsive and increasing braking impulse contributed to decreasing net anterior-posterior impulses up to around step 15 of a maximal sprint that increases in braking impulses after step 15 were the main factor resulting in a decreased anterior-posterior impulse.

The sprint literature agrees that a sprinters' performance during the initial acceleration and transition phase is determined by the net anterior-posterior and propulsive impulses applied during ground contact (Mero, 1987; Hunter et al., 2005; Kawamori, Nosaka & Newton, 2013; Morin et al., 2015). Furthermore, the authors generally reported that braking impulses were not significantly correlated to performance (Hunter et al., 2005; Kawamori et al., 2013 Morin et al., 2015). However, when performing a multiple regression analysis, Hunter et al. (2005) reported that although propulsive impulses accounted for 57% of the differences they observed, a small amount (7%) was attributed to the differences in braking impulses, although the authors could not rule out whether faster sprinters decreased braking forces.

Morin et al. (2015) distinguished between braking and propulsive impulses over multiple steps. This study was an extension of the Rabita et al. (2015) study (discussed later) to investigate the relationship between net anterior-posterior, braking, propulsive and vertical impulses over multiple steps to acceleration performance (i.e. mean 40 m velocity). The authors reported that net anteriorposterior impulse and propulsive impulse were significantly correlated to the 40 m velocity (r= 0.868, p<0.01 and r=0.802, P<0.01) while braking impulse was not. They also found that when splitting the 40 m sprint into two sections (i.e. 0-20m and 20-40 m), that average propulsive impulses over 0-20 m were significantly correlated (r = 0.833, P<0.02) with 40 m performance while 20-40 m data was not. The authors concluded that these result shows that faster sprinters had larger propulsive impulses but not necessarily lower braking impulses than slower ones. Furthermore, the fact that the mean data over the 0-20 m distance correlated strongly with performance while the data over the 20-40 m distance did not show the importance of generating as much anterior-posterior impulse as possible during the initial steps a sprint (Morin et al., 2015). While the study did not find any significant correlations between the performance variable and braking forces, the study highlighted that step-to-step decreases in net anterior-posterior impulse over the first six to seven steps were mainly due to decreases in the propulsive impulse, while between steps nine to 11 braking impulses were responsible for the larger decreases in net anterior-posterior impulse. This conclusion was recently supported by Nagahara, Mizutani, Matsuo, Kanehisa & Fukunaga (2017a) who reported that larger propulsive impulses provided a significant contribution to acceleration performance between 55% to 95% of maximal velocity while smaller braking impulses significantly influenced acceleration performance between 75% to 95% of maximal velocity (from  $7.5 \pm 0.6$  m into a sprint). This may suggest that during the acceleration phase sprinters should attempt to maximise propulsive impulses during the initial acceleration phase and then focus on minimising braking impulses during the transition and maximal velocity phases.

The results of Hunter et al. (2005) and Kawamori et al. (2013) suggest that during the early steps of a sprint, braking and vertical impulse generated are not as influential to performance compared to the net anterior-posterior or propulsive forces. The studies by Morin et al. (2015), Yu et al. (2016), Nagahara et al. (2016) and Nagahara, Naito, Morin & Zushi, 2014 however suggest that braking impulse may present a limiting factor to further increases in velocities at higher running velocities. Furthermore, although it has been accepted that braking forces are necessary in sprinting (e.g. storage of elastic energy) (Cavagna, Komarek &

Mazzoleni, 1971; Hunter et al., 2005), various authors have suggested that these forces should be minimised to improve sprint performance (Mero et al., 1992; Hay, 1994; Hunter et al., 2005). Previous literature has suggested that the anterior-posterior foot velocity prior to touchdown is the main contributor to the braking forces (Hay, 1994) and it is suggested that sprinters should aim to minimise the forward velocity of the foot immediately prior to touchdown (Mann & Sprague, 1983). Hunter et al. (2005) showed that during the transition phase in sprinting, smaller forward velocities of the foot prior to touchdown were associated with lower braking forces. While even world-class sprinters have some amount of forward foot velocity (Mann, 2007) faster sprinters are generally able to reduce the forward foot velocities more than slower sprinters (Ae et al., 1992; Mann, 2007). There is however still a lack of evidence linking the velocity of the foot prior to touchdown to braking forces.

Although previous studies only found weak (Hunter et al., 2005) or non-significant (Kawamori et al., 2013; Morin et al., 2015) relationships between vertical impulse and sprint performance during the acceleration phase. Interestingly, Nagahara et al. (2017a) reported that during the acceleration phase (<95% maximal velocity) smaller vertical impulses were associated with better acceleration performances. These results further support the suggestion by Hunter et al. (2005) that sprinters need to apply the necessary vertical impulse to overcome gravity and prepare for the next flight phase, with larger vertical impulses leading to longer flight times and therefore lower step frequencies (Nagahara, Mizutani, Matsuo, Kanehisa & Fukunaga, 2017a). The ever-decreasing contact times as running velocities, increase means that there is an increased demand to generate higher magnitudes of vertical ground reaction forces (Weyand et al., 2000; Weyand et al., 2010 Nagahara et al., 2017a). Nagahara et al., (2017a) showed that although vertical impulses did not change much during the acceleration phase, the mean vertical force applied during ground contact increased throughout the acceleration phase. Although producing relatively high levels of anterior-posterior force as velocities increase is essential to continue to increase running velocity (Rabita et al., 2015), the requirement to produce larger ground reaction forces during short contact times may represent a further limiting factor for some sprinters to maximise their running velocities (Weyand et al., 2000; Weyand et al., 2010). Furthermore, sprinters have unique GRF profiles compared to non-sprinters (Clark & Weyand, 2014). Clark and Weyand (2014) found that sprinters attained higher maximal velocities by applying significantly greater vertical forces during the first half of stance (2.65  $\pm$  0.05 BW vs. 2.21  $\pm$  0.05 BW) while there were no differences during the second half of stance (1.71  $\pm$  0.04 BW vs. 1.73  $\pm$  0.04 BW). This could be attributed to their ability to produce higher downward foot velocities prior to touchdown (Clark & Weyand, 2014). This is possibly aided by the higher knee lift generally achieved by better sprinters at the end of the recovery phase of swing (Mann, 2007).

To quantify a sprinter's ability to orientate ground reaction forces more horizontally, Morin, Eduard and Samozino (2011) proposed a measure quantifying the ratio of force application (RF) as the ratio of the anterior-posterior to resultant force during ground contact. Later, Morin et al. (2012) reported that a sprinter's dominance during sprint acceleration is not necessarily a result of the magnitude of the forces they can apply but rather a technical ability to properly direct forces during ground contact. The authors found that athletes with better acceleration ability produced more horizontally directed force with respect to the resultant force (larger RF) during a maximal sprint acceleration on a motorised treadmill. The mean RF value obtained from the treadmill was also a stronger determinant of the athletes' 100 m performance while the magnitudes of either vertical or resultant ground reaction forces were not. Rabita et al. (2015) later confirmed these results when investigating the mechanics of over ground maximal sprinting by constructing a virtual 40 m sprint by combining data from steps collected over multiple trials.

Morin et al., (2012) also suggested an index of force application technique ( $D_{RF}$ ). This was based on the slope created by individual RF values plotted over time. A steep slope or high  $D_{RF}$  means that a desired RF was not maintained while a flat RF-velocity relationship or small  $D_{RF}$  indicates a technical ability to maintain a desired RF ratio. This  $D_{RF}$  index revealed a further characteristic of world-class sprinters. It was reported that world-class sprinters have the ability to apply greater anterior-posterior forces at higher velocities (Morin et al., 2012; Rabita et al., 2015). This increased ability to produce greater anterior-posterior forces during higher sprinting velocities was found to be significantly correlated to their technical ability (a high RF) to direct the resultant ground reaction force vector more horizontally (Morin et al., 2012; Rabita et al., 2015).

Force application ability has been highlighted as an important characteristic of elite sprinters (e.g. Morin et al., 2012; Rabita et al., 2015). It was speculated that an increased hip extension and the ankle plantar flexors are important contributors to a better orientation of the resultant GRF vector (Rabita et al., 2015). Furthermore, various authors (e.g. Mann & Sprague, 1980; Wiemann & Tidow, 1995) proposed the theory that a clockwise rotation of the thigh generated by powerful hip extension is an important contributor to large anterior-posterior GRF production. The "hip extension theory" (Hunter et al., 2004c, p. 1445) could however not be supported by work from Hunter et al. (2004c) and Kugler and Janshen (2010). While Hunter et al. (2004c) showed that during the first half of stance, the hip extensor moment was the main contributor to the clockwise rotation of the thigh. Anterior-posterior ground reaction forces during this time were however generally low (Hunter et al., 2004c). Kugler and Janshen (2010) reported that at similar CM angles, faster sprinters did not generate larger propulsive forces than slower sprinters. This may be linked to a constraint that requires the sum of the moments about the CM to be zero, therefore ensuring postural stability throughout ground contact (Kugler & Janshen, 2010). Faster sprinters were able to achieve small CM angles and therefore larger anterior-posterior forces towards toe-off (Kugler & Janshen, 2010). This finding by Kugler and Janshen (2010) aligns with the mechanical relationship between CM acceleration and CM angle described by di Prampero et al. (2005). These results suggest the importance of the orientation of the body in sprinting.

## 2.3.3.1 Summary of external kinetics

The net anterior-posterior and propulsive impulse are the main determinants of acceleration ability during the initial acceleration and transition phases. Recent studies have shown that world class sprinters have a better technical ability to maintain a higher ratio of anterior-posterior to vertical ground reaction force throughout the acceleration phase compared to athletes with similar physical capabilities (Morin et al., 2011; Rabita et al., 2015). As sprinters accelerate from lower velocities to higher velocities, performance is influenced by the sprinters' ability to continue to produce a net anterior-posterior propulsive force (Rabita et al., 2015) while producing sufficiently large vertical forces to provide an appropriate flight time to allow the sprinter to prepare for the next stance phase (Hunter et al., 2005). However, vertical force production at higher velocities could be considered a

limiting factor as sprinters need to be able to generate sufficiently large vertical impulse during short ground contact times in order to maximise running velocities (Weyand et al., 2000). Evidence from recent literature suggests that the orientation of the body plays an important role in the performance of a sprinter during the acceleration phase in sporting.

#### 2.3.3 Musculoskeletal aspects of technique

#### 2.3.3.1 Joint Kinetics

So far, the literature review has presented kinematic and external kinetic data of the initial acceleration phase, transition phase and maximal velocity phase of a sprint. While this provides a description of the motion of a sprinter, the translation of the CM is ultimately driven by forces acting around the joints of the body (Jacobs & van Ingen Schenau, 1992). A joint kinetic analysis has the potential to provide a more in-depth understanding of muscle actions across a joint (Winter, 2009). Joint kinetics have previously been presented for step one (Charalambous et al., 2012; Debaere, Delecluse et al., 2013; Bezodis et al., 2014; Brazil, Exell, Wilson, Willwacher, Bezodis & Irwin, 2016), step two (Jacobs & von Ingen Schenau, 1992; Debaere, Delecluse et al., 2013), 12 m (Yu et al., 2016), ~ 14 m (Hunter et al., 2004c; Yu), ~35 m (Johnson & Buckley, 2001) and the maximal velocity phase (Bezodis et al., 2008; Yu et al., 2016). The following section will provide a review of the current literature regarding joint kinetics in sprinting. The first joint that will be discussed is the metatarsophalangeal (MTP) joint, followed by the ankle, knee and hip joints. However, since not all previous research have presented their data using the same units, the joint moment and joint power data from previous studies were adjusted to dimensionless values according to methods outlines by Hof (1996) and Bezodis, Salo & Trewartha (2010). This was achieved by using the mean participant height and mass data presented in each individual study.

With the MTP being closest joint to the ground it is exposed to large external forces and is therefore be considered an important contributor to the overall power output of the leg (Stefanyshyn & Nigg, 1997). Despite this few authors (Elftman, 1940; Stefanyshyn & Nigg, 1997; Smith, Lake & Lees, 2014; Bezodis et al., 2014) have investigated the joint kinetics of the MTP joint in sprinting. Generally, a plantar flexor moment has been observed at this joint during the first step of a sprint (Bezodis et al., 2012; Bezodis et al., 2014) and 15 m to 20 m into an acceleration phase (Stefanyshyn & Nigg, 1997; Smith et al., 2014). These studies have reported relatively large plantar flexor moments of 0.07 – 0.16 during the first stance (Bezodis et al., 2012) and 0.09 at a distance of 15 to 20 m into a sprint (Stefanyshyn & Nigg, 1997). Although a plantar flexor moment was present throughout stance, this joint acts predominantly as a power absorber for the majority of stance with magnitudes up to 12 to 35 times larger than power generation (Stefanyshyn & Nigg, 1997). It must be acknowledged that the specific source of the MTP joint moment cannot be isolated with standard inverse dynamics analysis and the joint moment observed at this joint are possibly due to a combination of flexor muscle, passive biological structures (e.g. fascia) and non-biological structures (e.g. sprint shoe stiffness) (Bezodis et al., 2014; Smith et al., 2014).

A period of dorsiflexion followed by plantar flexion was observed at the ankle during various steps throughout a sprint (Charalambous et al., 2012; Hunter et al., 2004c; Bezodis et al., 2008). This dorsiflexion range of motion was reported to increase between the initial acceleration and maximal velocity phases (Braunstein, Goldmann, Albracht, Sanno, Willwacher, Heinrich, & Brüggemann, 2013). Similar to the MTP joint moment, a plantar flexor moment is observed thorough stance. Plantar flexor moments previously reported at the ankle joint were 0.20 to 0.24 (Bezodis et al., 2012) and 0.24  $\pm$  0.01 (Charalambous et. al., 2011) on step one, 0.17 for step two (Jacobs & van Ingen Schenau, 1992), 0.27 (Johnson & Buckley, 2001) and 0.17 (Yu et al., 2016) from the transition phase (mid-acceleration) and 0.19 (Yu et al., 2016) to 0.25 (Bezodis et al., 2008) for the maximal velocity phase.

A recent study by Kulmala, Korhonen, Ruggiero, Kuitunen, Suominen, Heinonen, Mikkola & Avela (2016) compared how close to their maximal capacity the muscles surrounding the ankle and knee joint function during walking (1.6 m·s<sup>-1</sup>), running (4.1 m·s<sup>-1</sup>) and sprinting (9.3 m·s<sup>-1</sup>). They presented the calculated joint moment during the different forms of locomotion relative to the joint moments calculated during a reference hopping test. The authors reported that during sprinting the joint moments calculated at the ankle functioned at a larger relative effort compared to the knee joint moment (96% vs. 76%) when compared to their respective joint moments in the hopping test. Furthermore, the relative effort at which the ankle joint

functioned increased between walking  $(35 \pm 6\%)$ , running  $(84 \pm 12\%)$  and sprinting  $(96 \pm 11\%)$  when compared to the reference hopping test. This supports the importance of the ankle moment to contributing to the forward and upward acceleration of the CM during sprinting (e.g. Cabral, Kepple, Moniz-Pereira, João & Veloso, 2013; Debaere et al., 2015; Koike & Nagai, 2015).

Across the various steps previously investigated, the negative ankle power phase ranged from the first 30% of stance during step one (Charalambous et al., 2012) to 60% of stance during maximal velocity phase (Bezodis et al., 2008). Unlike the MTP joint, the ankle joint generated 3.3 to 4.0 times more energy during the first step than it absorbed (Bezodis et al., 2014). Bezodis et al. (2014) reported magnitudes of energy absorption between -0.041 and -0.067 and energy generated between 0.163 and 0.223. However, during the maximal velocity phase, Bezodis et al. (2008) reported that energy absorbed (-0.093) at the ankle outweighed energy generated (0.053). These contradictory findings are likely due to the differences in the absolute durations of the negative and positive power phases, joint angular velocities and joint moments between different steps during sprinting. Nonetheless, these findings across different studies suggest that there may be an increased requirement to absorb energy at the ankle and maintain the height of the centre of mass following touchdown. Interestingly, a study comparing the positive and negative work done at the ankle between acceleration and steady state running within the same participants reported that negative and positive work done at the ankle joint did not significantly change between the two conditions (Williams III, Cole & Powell, 2017). This may suggest that the ankle joint is not an important contributor to acceleration performance (Williams III et al., 2017). However, the protocol used involved sub-maximal steady state and accelerated running. It is therefore unclear if a maximal acceleration and steady state running task will show similar results.

Although the knee joint moment time-histories have shown inconsistencies in the previous literature, lower knee moments were generally reported relative to ankle and hip moments (Charalambous et al., 2012; Bezodis et al., 2008). These differences in knee moment patterns are characterised by high frequency fluctuations between a knee flexor and knee extensor moment soon after touchdown (Johnson & Buckley, 2001; Hunter et al., 2004c; Bezodis et al., 2008; Yu et al.,

2016). The high frequency fluctuation soon after touchdown may have been influenced by the filtering methods used when calculating the joint kinetics (Bisseling & Hof, 2006; Bezodis et al., 2013). This makes it difficult to compare the results of different studies. The different methods of filtering kinematic and kinetic data for joint kinetic calculations will be discussed in section 2.4.3.1.

Immediately following touchdown, a knee flexor joint moment was typically reported in most studies in sprinting (e.g. Mann & Sprague, 1980; Jacobs & van Ingen Schenau, 1992; Johnson & Buckley, 2001; Bezodis et al., 2008; Charalambous et al., 2012; Bezodis et al., 2014; Yu et al., 2016). These knee flexion moments immediately following touchdown were generally larger during the transition (Johnson & Buckley, 2001; Hunter et al., 2004c; Yu et al., 2016) and maximal velocity (Bezodis et al., 2014; Yu et al., 2016) phases compared to the first few steps of a sprint (Jacobs & van Ingen Schenau, 1992; Charalambous et al., 2011; Bezodis et al., 2014; Brazil et al., 2016). This knee flexor moment following touchdown was previously associated with the action of attempting to decrease the influence of braking forces (Mann & Sprague, 1980; Mann, 1981) and therefore the knee flexor moment may increase with increasing touchdown distances.

Ignoring any fluctuations in the knee moment time-histories following touchdown, previously reported peak resultant knee extension moments were 0.05 to 0.25 (Bezodis et al., 2014) and  $0.33 \pm 0.07$  (Brazil et al., 2016) for step one, 0.10 for step two (Jacobs & van Ingen Schenau, 1992), 0.19 (Johnson & Buckley, 2001) and 0.10 (Yu et al., 2016) from the transition phase and 0.09 (Bezodis et al., 2008) and 0.12 (Yu et al., 2016) for the maximal velocity phase. Furthermore, Yu et al. (2016) reported that within the same group of participants, that the peak knee extensor moment significantly increased between the transition and maximal velocity phases (p = 0.001). The knee joint has been suggested to play a potentially important role in generating anterior-posterior and vertical velocity during the initial acceleration phase (Charalambous et al., 2012b; Debaere, Delecluse et al., 2013; Bezodis et al., 2014). During the transition and maximal velocity phases the knee joint and muscles surrounding the knee are thought to play more of a supportive role assisting with the transfer of energy to the more distal joints (Bezodis et al., 2008; Johnson & Buckley, 2001).

These different functional roles of the knee joint moment could be further highlighted by relatively large positive power phases reported at the knee between the initial acceleration, transition and maximal velocity phases. The large positive power phases reported during the first few steps of the sprint highlights the knee joint moments' importance to accelerating the sprinter (Bezodis et al., 2014). On the other hand, a negative power phase followed by a positive power phase has been reported at the knee during the transition and maximal velocity phases (Johnson & Buckley, 2001; Hunter et al., 2004c; Bezodis et al., 2008), which suggests that the knee extensor moment is important to slow the downward velocity of the CM following touchdown before accelerating the sprinter into the next flight phase (Mann, 1981). This supports the proposal that during the transition and maximal velocity phases, the knee extensor moment plays a role in maintaining the height of the CM during ground contact (Johnson & Buckley, 2001).

The action of the hip extensor muscles around the hip are often thought to be performance determining in the sprint (Hunter et al., 2004c) with the "hip extension" theory" (Hunter et al., 2004c; p.1445) describing the importance of the hip in generating propulsive GRF during ground contact (Mann & Sprague, 1980; Wiemann & Tidow, 1995; Hunter et al., 2004c). Across the initial acceleration, transition and maximal velocity phases a resultant extension moment was observed at the hip during first two thirds of stance (Johnson & Buckley, 2001; Hunter et al., 2004c; Bezodis et al., 2008; Charalambous et al., 2012; Bezodis et al., 2014) after which a resultant hip flexor moment was observed. Peak hip extension moment values were previously reported for the first step  $(0.20 \pm 0.01)$ : Charalambous et al., 2012; 0.13 to 0.17: Bezodis et al., 2014), steps of the transition phase (0.24: Yu et al., 2016; 0.31: Johnson & Buckley, 2001) and the maximal velocity phase (0.19; Bezodis et al., 2008; 0.26: Yu et al., 2016). Since the hip extends throughout stance, the hip power patterns mimics that of the hip moment pattern. This resulted in a large power generation phase during the first two thirds of stance followed by a power absorption phase during the last third of stance, which likely acts to slow the clockwise rotation of the thigh and prepare for the upcoming swing phase (Charalambous et al., 2012). During the first stance, around 4.5 times more energy was generated than absorbed (Bezodis et al., 2014). During maximal velocity phase only about 1.5 times more energy was generated at the hip than was absorbed (Bezodis et al., 2008). Williams III et al. (2017) recently reported this decrease in positive work at the hip within the same group of participants. The authors reported that the positive work done at the hip decreased between an accelerated ( $0.06 \pm 0.02$ ) running task and a steady state running task ( $0.04 \pm 0.02$ ) (Williams III et al., 2017). The authors suggested that a focus on hip extension strength may be important to improve performance during accelerating running tasks, but this was not specific to a maximal sprint acceleration.

Previously, some studies (e.g. Belli, Kyröläinen & Komi, 2001; Kyröläinen, Belli & Komi, 2001; Kuitunen, Komi & Kyröläinen, 2002; Schache, Blanch, Dorn, Brown, Rosemond & Pandy, 2011) reported changes in joint kinetics over a range of steady state running velocities. While these studies are not representative of a maximal sprint acceleration, they could offer some insights into the musculoskeletal requirements of running at progressively higher velocities. Generally, there was an increase in work done at the ankle joint (Belli et al., 2001; Schache et al., 2011) and knee joint (Belli et al., 2001) during the stance phases as velocity increased. However, only the results from Schache et al. (2011) showed that this was accompanied by an increase in ankle moments at lower velocities (e.g.  $3.50 \pm 0.04$  $m \cdot s^{-1}$  to 5.02 ± 0.10  $m \cdot s^{-1}$ ). This may be due to differences in the sub-maximal running velocities and differences in running techniques of the participants used in different studies. Belli et al. (2001) suggested that the increased work at the ankle and knee as velocities increased may have been important to increase joint stiffness at the knee and ankle with increasing steady state running velocities. This increased lower body stiffness would have facilitated the application of large vertical GRFs immediately following touchdown (Clark & Weyand, 2014) and shortened ground contact times to facilitate larger running velocities (Kuitunen et al., 2002). At the hip, increases in hip extensor moments following touchdown increased as steady state running velocities increased (Belli et al., 2001; Kuitunen et al., 2002; Schache et al., 2011). This has been interpreted as showing the importance of the hip extensors as the primary forward movers during sprinting (Belli et al., 2001; Kuitunen et al., 2002). However, it is unclear whether the results from these studies can be directly transferred to sprinting tasks where the participants are accelerating maximally. For example, while running at lower steady state running velocities could represent a controlled sub maximal activity to achieve the desired running velocity, maximal accelerated sprinting requires maximal effort to maximise the change in centre of mass velocity. Changes in joint kinetics during maximal accelerated sprinting therefore requires further investigation.

# 2.3.3.2 Theoretical investigations into sprinting technique

Theoretical investigations have previously been used to further understanding of kinematic and kinetic aspects of sprinting mechanics. Generally, these have been developed using empirical data (e.g. Bezodis, Trewartha & Salo, 2015; Debaere, Delecluse, Aerenhouts, Hagman & Jonkers, 2015) and have investigated the influence or contribution of kinematic and joint kinetic variables in sprinting. By developing a simulation model, Bezodis et al. (2015) examined how manipulations of certain kinematic variables previously reported in empirical research (e.g. Bezodis et al., 2008; Kugler & Janshen, 2010; Charalambous et. al., 2012; Bezodis et al., 2014) influence performance during the first stance phase in sprinting. The variables that were manipulated included touchdown distances and ankle joint dorsiflexion during early stance (Bezodis et al., 2015). Specifically, the study by Bezodis et al. (2015) provided evidence for the beneficial effect of decreasing touchdown distances (i.e. foot placed further backwards relative to CM) and decreasing the ankle dorsiflexion range of motion during the first stance in sprinting. However, limits to increases in performance resulting from too large a decrease touchdown distances were found (Bezodis et al., 2015). Through the development and application of a simulation model in sprinting Bezodis et al. (2015) provided a more in depth understanding of the influence of kinematic features on sprint performance.

Although kinematics play an important role in sprinting, the forces and joint moments acting on the body ultimately generate angular motion of the segments and accelerate the centre of mass of the sprinter. The contributions by joint moments to CM acceleration in sprinting have previously been reported for the stance phase (e.g. Cabral, Kepple, Moniz-Pereira, João & Veloso, 2013; Debaere et al., 2015; Koike & Nagai, 2015) and swing phase (e.g. Koike & Sudo, 2015) of sprinting. The majority of these studies (i.e. Cabral, Kepple, Moniz-Pereira, João and Veloso, 2013; Koike & Nagai, 2015; Koike & Sudo, 2015) have however only presented limited data in abstract form. Furthermore, studies that have investigated the contributions to CM acceleration during the stance phase of sprinting have generally

focused on the contributions to the whole-body CM during the initial acceleration phase in sprinting. Nevertheless, these studies are generally in agreement that the plantar flexor joint moments at the ankle induces the largest forward (Cabral et al., 2013; Debaere et al., 2015; Koike & Nagai, 2015) and upward (Cabral et al., 2013; Debaere et al., 2015) accelerations on the CM.

The contributions to CM accelerations by the hip and knee were relatively small compared to those of the ankle (Cabral et al., 2013; Debaere et al., 2015; Koike & Nagai, 2015). However, Debaere et al. (2015) did report larger vertical and anterior-posterior contributions by the hip and knee during the first stance phase compared to the second stance phase in sprinting. This may have been influenced by the changes in posture between steps one and two (Debaere et al., 2015) and suggests that the hip extensors may be better able to contribute to the anterior-posterior acceleration of the CM during the early steps in sprinting when the body is in a less inclined position compared to maximal velocity sprinting.

The ability of the proximal hip and knee joint moments to accelerate the CM is likely determined by the distal ankle moment. Cabral et al. (2013) identified that the contribution by the hip joint moment during early stance increased when they limited the position of the foot relative to the ground. The authors concluded that the plantar flexors at the ankle are crucial to performance during the first step in sprinting as they directly accelerate the CM while also playing a stabilising role at the foot, therefore providing a stable base for the more proximal joint moments to act on (Cabral et al. 2013). Koike and Nagai (2015) reported that the hip extensors and to a lesser degree the knee extensors contributed to the ankle joint moment during the ankles' negative power phase.

The ability of the hip and knee to contribute to the forward acceleration of the CM therefore appears to be linked to the posture (Debaere et al., 2015) of the sprinter and the ability of the plantar flexors at the ankle to transfer forces to the ground (Cabral et al. 2013; Koike & Nagai, 2015). While the joint moments have generally been reported as the main contributors to CM acceleration during stance, Koike and Sudo (2015) identified the motion dependent term (i.e. product sum of the segment angular velocities) as the main contributor to knee joint angular velocity. The motion

dependent term has also previously been identified as an important contributor to performance where end-point velocity (i.e. tennis, baseball pitching) is of importance (e.g. Koike & Harada, 2014; Hirashima, 2011). This variable may therefore play an important role during the late swing phase, when the backward velocity of the foot relative to the CM is maximised prior to touchdown. The joint moments, however indirectly, contribute to high end-point accelerations by contributing to the motion dependent term (Koike & Harada, 2014).

# 2.3.3.3 Summary of musculoskeletal aspects of technique

Previous research investigating the musculoskeletal demands of sprinting have generally focused on a specific step or phase of the sprint. The few studies that have reported joint kinetics data across multiple steps of a maximal accelerated sprint have indicated some important changes in the energy absorption and generation strategies (Ito et al., 1992; Braunstein et al., 2013) and joint moments (Yu et al., 2016) at the ankle and knee. The results presented in these studies suggest that as sprinters progress towards maximal velocity, a pattern of increased energy absorption and decreased energy generation appears to emerge. However, these multi-step studies have either only reported general trends in abstract form (e.g. Ito et al., 1992; Braunstein et al., 2013) or only focused on net joint moments (Yu et al., 2016). The data presented thus far have provided an invaluable insight into the demands of sprinting during individual steps, but it is difficult to identify any patterns of changing initial acceleration phase, transition phase and maximal velocity phase joint kinetics. With the performance of a sprinter is largely determined by the work done at the joint of the stance limb, a better understanding of the changes in joint kinematic and kinetics will add valuable knowledge to better understanding the challenges sprinters face during maximal sprinting.

Some studies have directly quantified the influence of kinematics and joint kinetics of technique on performance. Although these studies have reported data from single steps or from steps within the initial acceleration phase of sprinting, they have increased understanding of the contributing factors to performance. However it is not known how musculoskeletal demands and the contributions to performance change across a sprint. Knowledge of these changes will provide new insight into the acceleration phase during maximal sprinting.
# 2.4 Methodological considerations

## 2.4.1 Methods of Data collection

# 2.4.1.1 Video based motion analysis

Video has traditionally been one of the most popular measurement techniques for the analysis of human motion (Payton, 2008). Manual video analysis involves the recording of motion trials without the need to attach markers to the participants. Despite being time consuming to the researcher, manual video analysis offers an unobtrusive and externally valid method to collect motion data from well-trained athletes. In sprinting, manual digitising has been a widely used data collection procedure (e.g. Mann & Sprague, 1980; Mann & Herman, 1985; Johnson & Buckley, 2001; Bezodis et al., 2008; Bezodis et al., 2014). Ultimately, it is important that motion analysis needs to provide an accurate estimation of position data (Brewin & Kerwin, 2003). The accuracy of a system is generally assessed by comparing the estimated coordinate to known locations (Challis & Kerwin, 1992). The set-up of the camera plays an important role in ensuring that accurate and valid data is collected. Generally, the distance between the camera and the performer needs to be maximised and the camera needs to be set-up orthogonal to the path of the movement being recorded. This will ensure that perspective error is minimised (Payton, 2008). Furthermore, the field of view needs to be adapted to capture the full range of motion with the addition of a few extra frames before and after the skill (Robertson & Caldwell, 2014). With the image of the performer as large as possible within the field of view, care should also be taken not to digitise too close to the edges of the fields of view as this can result in distorted image data (Robertson & Caldwell, 2014).

# 2.4.1.2 Ground reaction forces

Force at the foot-ground interface can be either estimated using kinematic data and complex mathematical formulae or directly measured using force plates imbedded in the ground (Lees & Lake, 2008). Data from force plates have played an important role in furthering understanding of the interaction between the athlete and external environment and facilitating the calculation of joint kinetics using inverse dynamics (Exell, Gittoes, Irwin & Kerwin, 2012). A difficulty with collecting ground reaction force data using force plates is the need for foot contact to occur within the relatively small area of the force plate (typically 0.90 × 0.60 m). With the typical dimensions

of a force plate shorter than the average step length and only about twice the width of the steps previously reported during the initial acceleration phase ( $\sim 0.3 - 0.4$  m; Ito, Ichikawa, Isoletho & Komi, 2006), occurrence of foot contacts outside of the boundaries of the force plates can lead to rejected trials (Johnson & Buckley, 2001). This can affect the number of trials needed to collect sufficient data and therefore fatigue could start to influence the data if a lot of trials are required. Even if ground contact occurred within the boundaries of the forces plate, errors in the calculation of the centre of pressure (COP), which is a variable needed for the calculation of the joint kinetics, increases as contacts occur towards the corners of the force plate and outside the force sensors (Bobbert & Schamhardt, 1990).

Using two force plates mounted end-to-end, Exell et al., (2012) reported that the trial success rate increased to 87% compared to 35% when only one force plate was used. Furthermore, Exell et al. (2012) reported that errors in COP calculations associated with foot contacts that occurred across two force plates were within  $0.003 \pm 0.002$  m of a control. The authors noted that these errors are acceptably small and that trials where foot contact occurred across two plates could and should be included in inverse dynamics calculations.

Intentionally altering step parameters to ensure contact is made with the forces plates has previously been shown to influence the timing and magnitudes of ground reaction force variable (Challis, 2001). To overcome the effect of force plate targeting, previous studies have used trials were sprinters did not noticeably alter their step characteristics whilst approaching the force plates (Johnson & Buckley, 2001; Hunter et al., 2004a; Bezodis et al., 2008). Another approach used previously was to place a check mark before the sprinter enters the data collection zone (Mann, 1981; Bezodis et al., 2008). Mann (1981) found that this increased the number of successful contacts on the force plate. The occurrence of successful trials can therefore be increased by using two force plates in sequence and ensuring the participants start their sprints at an appropriate distance from the force plates depending on the step required for investigation.

### 2.4.2 Signal Processing

### 2.4.2.1 Coordinate Reconstruction

After collecting and digitising image data (in pixels), these data need to be transformed into real-world locations (e.g. in metres). Two methods used to transform image data to real-world locations are scaling and direct linear transformation (Brewin & Kerwin, 2003). Due to the planar nature of sprinting, some studies have applied scaling techniques (e.g. Johnson & van Ingen Schenau, 1992; Johnson & Buckley, 2001; Bezodis et al., 2014). Advantages of scaling are the simplicity of use and uncomplicated mathematical procedure (Brewin & Kerwin, 2003). This method however has the potential to result in larger errors in data reconstruction when cameras are not set-up exactly level and perpendicular to the plane of motion (Brewin & Kerwin, 2003).

Direct linear transformation (DLT) is another method that is commonly used in video analysis. DLT allows greater flexibility in camera set-up and has been shown to offer greater accuracies in coordinate reconstruction (Brewin & Kerwin, 2003). A modified two-dimensional direct linear transformation (2D-DLT) (Walton, 1981) can be used to reconstruct motion occurring in a single plane. The method uses a minimum of eight parameters, which are used to transform the digitised image coordinates into real-world coordinates. A minimum of four calibration points are required to calculate these eight parameters, although increasing the number of points has been shown to increase the reconstruction accuracy (Mclean, Vint, Hinrichs, DeWitt, Morrison & Mitchell, 2004). Further, reconstruction accuracies are greater if the reconstructed points lie within the area defined by the calibration points (Challis & Kerwin, 1992). It is therefore necessary to ensure that the calibration point are evenly spread throughout the field of view of the camera. Brewin and Kerwin (2003) demonstrated greater errors for reconstructed points which lie outside the calibration points. To further enhance reconstruction accuracy and account for the image distortion due to the curvature of the lens (Brewin & Kerwin, 2003) a ninth parameter can be calculated (Walton, 1981).

# 2.4.2.2 Noise Reduction

Kinematic and kinetic data is composed of the true signal and noise (Challis, 1999). The noise in the data, which could be influenced by the spatial precision of the digitising system, incorrect digitisation, lighting, electrical interference, or artefacts from moving wires has different characteristics from the signal (Derrick, 2014). When differentiating the signal, the noise contained within the signal is amplified and even minimal noise contained within the displacement data can have a large effect on velocity and acceleration data (Wood, 1982). Because the noise is nondeterministic, has a lower amplitude and often has a different frequency range compared to the true signal it can be minimised within the data (Derrick, 2014). The techniques used for smoothing data include polynomial smoothing, splines, Fourier smoothing, moving average, digital filtering and generalised cross-validation (Derrick, 2014).

Digital filters are often used on biomechanical data. This type of filter allows the selective attenuation of noise at certain frequencies (Winter, 2009). Since most of the noise in biomechanical analysis is high frequency in nature the low-pass Butterworth filter is commonly used in biomechanical data analysis (Derrick, 2014). This type of filter allows low frequency data to pass through the filter unchanged. Data is usually passed bi-directionally through the filter, so any time shift created by the first pass is removed (Derrick, 2014). Digital filters generally distort the data at the beginning and end of the data set. This can be minimised by ensuring that extra data is collected at the start and end of the trial or the ends are padded with data (Derrick, 2014). Furthermore, using a low pass filter in combination with data differentiation via a central differences method offers an appropriate solution to approximating an acceleration trace from displacement data (Wood, 1982).

When using digital filters, the selection of the optimal cut-off frequency is important since noise should be attenuated whilst minimising distortion of the true signal. To determine the optimal cut-off frequency, various methods have previously been suggested including residual analysis (Winter, 2009) and autocorrelation analysis (Challis, 1999). Residual analysis determines the optimal cut-off frequency by calculating the root-mean squared difference between filtered and unfiltered signals over a range of frequencies (Winter, 2009). While being widely used, this method can be quite labour intensive and subjective as it requires residual plots to be visually assessed which could lead to a lack of repeatability (Challis, 1999). The autocorrelation method, which is based on the autocorrelation function, varies the

cut-off frequencies until a signal representing the difference between the filtered and unfiltered data represents the best approximation of white noise (Challis, 1999). While it is unclear whether different methods to identify optimal cut-off frequencies are superior, the auto correlation method proposed by Challis (1999) provides a more objective and repeatable method of determining the cut-off frequencies of multiple data sets however the filtered data should be investigated to identify any anomalies introduced during the filtering process (Challis, 1999).

## 2.4.3 Computational methods in biomechanics

### 2.4.3.1 Inverse dynamic analysis

The computation of internal joint forces, moments and joint powers is important to investigate the loading participants experience when executing their task. An inverse dynamics analysis (IDA) is an unobtrusive means to approximate the net moments, net powers and work at a joint using known inertial properties, kinematics and external ground reaction forces (Whittlesey & Robertson, 2014). Using Newton's second and third laws of motion, the forces and moments acting on the segments are calculated. An inverse dynamics analysis involves a process of working from known to unknown. Starting with the most distal segment (e.g. Foot segment), the inertial properties of that segment are combined to calculate the forces and moments acting at the proximal endpoint of the segment (Winter, 2009). This process is aided by the representation of the human body as a linked segment system. However, the choice of model playing an important role in the analysis (Hatze, 2000). This will be discussed in more detail in section 2.4.4.1.

The uncertainties associated with an IDA have been well documented in previous research (e.g. Challis & Kerwin, 1996; Holden & Stanhope, 1998; Hatze, 2000; Riemer, Hsiao-Wecksler & Zhang, 2007; Bezodis, Salo & Trewartha, 2013; Whittlesey & Robertson, 2014). These uncertainties are influenced by the accuracy of the inputs and data treatment techniques (e.g. filter) used to generate the data needed to perform an IDA. Generally, uncertainties in IDA are linked to errors contained within the ground reaction forces, centre of pressure, joint centre locations, segment inertial properties and accelerations (Hatze, 2000; Whittlesey & Robertson, 2014) as well as the techniques used to process the data prior to

performing the IDA (Bezodis et al., 2013). However, it has been suggested that some inputs (e.g. kinematics) have a larger influence on the uncertainties associated with IDA calculations than others do (e.g. GRF, segment inertial properties) (Challis & Kerwin, 1996; Riemer et al., 2007; Whittlesey & Robertson, 2014). Regarding the influence of the kinematic inputs on the uncertainty of the IDA data, joint centre locations (Challis & Kerwin, 1996) and the accelerations derived from the displacement data (Bezodis et al., 2013) are suggested to be the main sources of uncertainty.

The locations of joint centre are important for the IDA as they define the point at which the resultant joint forces and moments act. However, during motion analysis, the resulting motion of the segments may result in a variation of the instantaneous joint centre locations (Challis & Kerwin, 1996). Holden and Stanhope (1998) investigated the influence of knee joint location variation on the resulting joint moments. The authors reported that this variation was more influential during slower walking trials than faster walking trials. The authors concluded that during slower walking, when the knee joint moments were relatively small (i.e. smaller than the variation in the knee joint centre location), a confident interpretation of the knee moment as flexor or extensor dominant was not possible. The influence of walking speed as reported by Holden and Stanhope (1998) may be related to the magnitudes of the external ground reaction forces during these tasks. Whittlesey & Robertson (2014) noted that during the stance phases of locomotion, the GRF dominate the joint moment calculations and are therefore likely to be less influenced by uncertainties in the kinematic data. An accurate measurement of GRF is therefore essential to ensuring accurate IDA during ground contact. This is different to the swing phases, where the lack of external GRF means that the kinematic inputs have a larger effect on the IDA results (Whittlesey & Robertson, 2014).

When differentiating displacement data, the noise contained within these data are amplified resulting in noisy velocity and acceleration data (Winter, 2009). Data treatment (i.e. filtering) is therefore an important consideration to ensuring that the noise is sufficiently attenuated therefore decreasing the influence of noise in the acceleration data on the IDA uncertainties (see section 2.4.2.2). When performing an IDA the cut-off frequency used to filter the kinematic and kinetic data requires careful consideration. Previous authors have investigated the influence of using varying cut-off frequencies to filter the kinematic and GRF data used during the IDA (Bisseling & Hof, 2006; Kristianslund, Krosshaug & van den Bogert, 2012; Bezodis et al., 2013). Bezodis et al. (2013) noted that when filtering the kinematic data at lower cut-off frequencies compared to the kinetic data, that excessive high frequency artefacts in the knee joint moments were observed following touchdown. The lower cut-off frequencies used for the kinematic data likely attenuated the true accelerations at the lower limb around touchdown resulting in the creation of a large internal joint force to counter the higher frequency GRF data (Bezodis et al., 2013). Bisseling and Hof (2006), Kristianslund et al. (2012) and Bezodis et al. (2013) recommended filtering the GRF and kinematic data using the same cut-off frequency when used for an IDA. Although the cut-off frequency should be kept as high as possible to maintain as much of the impact GRFs as possible, the cut-off frequency ultimately depends on the quality of the kinematic data (Bezodis et al., 2013).

One limitation of IDA is that individual muscle activity cannot be determined (Whittlesey & Robertson, 2014). This is due to the indeterminacy problem were there are more muscle and forces than equations to solve for the unknowns (Whittlesey & Robertson, 2014). When interested in muscle actions, further methodologies are needed to decompose the joint moments and joint forces into individual muscle moments and forces (Whittlesey & Robertson, 2014). Furthermore, forces and joint moments acting on a segment within multi-articulated systems have the ability to accelerate not just the segments on which they are acting but all segments within a system (Zajac & Gordon, 1989). This makes the direct contributions by a force or joint moment to acceleration of the segments or the whole-body CM difficult to understand.

### 2.4.3.2 Induced acceleration analysis

Due to the dynamic coupling associated with the multi-articulated systems, forces and joint moments acting on one segment will induce joint reaction forces at each joint in the system (Zajac & Gordon, 1989). Mathematically, the equations of motion for a multi-articular body are coupled and as such, the accelerations resulting from distant forces can be determined (Zajac & Gordon, 1989). The equation of motion that governs a multi segment system is generally written as (Zajac & Gordon, 1989; Zatsiorsky, 2002a; Selbie, Hamill & Kepple, 2014):

$$M(\theta)\ddot{\theta} = JM_i + V(\theta, \dot{\theta})_i + G(\theta)_i$$
 [Equation 2.1]

where  $\theta$ ,  $\dot{\theta}$ ,  $\ddot{\theta}$  represent generalised coordinates, velocities and accelerations of the segments; M ( $\theta$ ) represents mass matrix of the system;  $JM_i$  is the vector of net joint moments;  $(G(\theta)_i + V(\theta, \dot{\theta})_i)$  represent gravity and velocity dependent terms and i represents the joint. Equation 2.1 can be expanded to describe a two segment system:

$$M_{11}(\theta)\ddot{\theta}_{1} + M_{12}(\theta)\ddot{\theta}_{2} = JM_{1} + V(\theta,\dot{\theta})_{11} + V(\theta,\dot{\theta})_{12} + G(\theta)_{11}$$
[Equation 2.2]  
$$M_{21}(\theta)\ddot{\theta}_{1} + M_{22}(\theta)\ddot{\theta}_{2} = JM_{2} + V(\theta,\dot{\theta})_{21} + V(\theta,\dot{\theta})_{22} + G(\theta)_{21}$$
[Equation 2.3]

Because equation 2.2 and equation 2.3 both contain acceleration components for both segments (i.e.  $\ddot{\theta}_1 and \ddot{\theta}_2$ ), they need to be solved in matrix form.

$$\begin{pmatrix} M_{11}(\theta) & M_{12}(\theta) \\ M_{21}(\theta) & M_{22}(\theta) \end{pmatrix} \begin{pmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{pmatrix} = \begin{pmatrix} \tau_1 \\ \tau_2 \end{pmatrix} + \begin{pmatrix} V(\theta, \dot{\theta})_{11} \\ V(\theta, \dot{\theta})_{21} \end{pmatrix} + \begin{pmatrix} G(\theta)_{11} \\ G(\theta)_{21} \end{pmatrix}$$
[Equation 2.4]

Equation 2.1 can be solved for accelerations ( $\ddot{\theta}$ ) by inverting the mass matrix ( $M(\theta)$ ):

$$\ddot{\boldsymbol{\theta}} = \boldsymbol{M}^{-1}(\boldsymbol{\theta}) \left[ \boldsymbol{J} \boldsymbol{M}_{i} + \boldsymbol{G}(\boldsymbol{\theta})_{i} + \boldsymbol{V}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}})_{i} \right]$$
[Equation 2.5]

Since Equation 2.5 represents a linear equation (i.e.  $A \times x = c$ ), the induced acceleration due to any input (i.e.  $JM_i$ ,  $G(\theta)_i$ ,  $V(\theta, \dot{\theta})_i$ ) can be solved at any instance in time. Furthermore, the above equations for a planar two segment system should demonstrate two important characteristics that underpin induced acceleration analysis. Firstly, the equations of motion for multiple segments are coupled and any force causing motion of one segment in a system will simultaneously accelerate all other segments within that system (Zajac & Gordon, 1989). The ability of force to accelerate remote segments is due to interaction forces which occur between all segments of a system when forces act on a system (Hirashima, 2011). Secondly, the accelerations produced by a force depend on the configuration ( $\theta$ ) of the system (Hirashima, 2011). In other words, the same force can cause different accelerations throughout the segments depending on how the segments are orientated relative to

each other. Therefore, while the magnitudes of the joint moments will influence the magnitude of the resulting accelerations, the pose of the system will influence the direction of the resulting accelerations (Hof & Otten, 2005). This method therefore has the potential to offer valuable insights into how joint moments and segment orientations contribute to CM acceleration in maximal sprinting.

Identifying these contributions to CM acceleration is known as an induced acceleration analysis (IAA) (Selbie et al., 2014). IAA is based on the dynamic coupling associated with multi-articulated bodies (Zajac & Gordon, 1989), and lies between the field of inverse dynamics and forward dynamics, since it can be used to interpret experimental or simulated data (Selbie et al., 2014). Because this method uses existing data to compute the induced accelerations, an IAA is easier to implement than a forward dynamics model but also allows the calculation of instantaneous induced accelerations. These induced accelerations fall into two categories. Firstly, the instantaneous effects which include all joint moment and gravity related accelerations at a particular instant and secondly the cumulative effects which include all induced accelerations due the velocity dependent forces (Hirashima, 2011). In tasks where the end-point velocity is high (e.g. baseball pitching, Hirashima, 2011) it is more difficult to identify the role of joint moments or gravity to the system's motion. This is because at each instant in time, joint moments and gravity not only induce instantaneous accelerations on the system, but also influence the system by contributing to the velocity dependent term (Hirashima, 2011).

While an IAA can provide an objective breakdown of movement dynamics, various authors have raised the issue that induced accelerations are sensitive to the modelling details (e.g. Chen, 2006; Patel, Talaty & Õunpuu, 2007) as well as modelling error associated with variations in segment lengths, joint axis fluctuation and errors in body segment parameters (Koike, Nakaya, Mori, Ishikawa& Willmott, 2017). This further extends into how the interaction between the model and the external world is described, as this has been previously shown to have an effect on the resulting whole-body induced acceleration results (Dorn, Lin & Pandy, 2010). Finally, it is important not just to consider the induced accelerations due to individual

forces, but rather the knowledge gained from studying the effects of individual forces should be combined to understand how they function as a unit (Chen, 2004).

## 2.4.3.3 Induced power analysis

The accelerations induced on a segments have the potential to change the energy of the segment. A muscle can influence the energy of a segment irrespective of whether it is performing a concentric, eccentric or isometric action (Zajac, Neptune & Kautz, 2002). Furthermore, due to dynamic coupling of multi-articulated systems, the energy of a segment can be increased or decreased by a joint moment acting on distant segments (Selbie et al., 2014). This is due to interaction forces between segments (Fregly & Zajac, 1996). The contribution of a joint moment or force to the energy of segments can be determined at each instant from the current state of the system (i.e. segment masses, segment velocities) and the induced segment accelerations due to the joint moments or other forces (Equation 2.6).

$$P_i = M_i(\theta)\ddot{\theta}_i \times \dot{\theta}_i$$

#### [Equation 2.6]

This is known as an induced power analysis (IPA) and provides a clear interpretation of how joint moments or other forces increase or decrease the energy of a segment (Zajac et al., 2002). If the current state of the system ( $\dot{\theta}_i$ ) is known, equation 2.6 defines the relationship between any force in the model and the power it contributes (positive or negative) to any segment (Fregly & Zajac, 1996).

### 2.4.4 Models used in biomechanics

Whether using inverse dynamics or forward dynamics analysis of human motion, a representative model of the musculoskeletal system must be used. These describe the spatial characteristics of the segments which make up the musculoskeletal system, the contact of the body with the ground and the inertial properties of the different segments within the musculoskeletal system.

# 2.4.4.1 Kinematic models

Kinematic models which represent "an abstract representation of selected attributes of a real object, event, or process" (Hatze, 2000, p. 110) are essential in biomechanics. While complex models are not very economical, the models used in biomechanics tend to be simplified to include the segments and joint deemed important for the skill under investigation (Bezodis, Salo & Trewartha, 2012). However, Hatze (2000) warned that oversimplification could lead to inaccurate results with "valid simplifications" necessary (Hatze, 2002, p. 110) to preserve the predictive, structural and replicative validity of the models. Biomechanical investigations in sprinting have generally modelled the stance leg as three rigid segments (e.g. Mann & Sprague, 1980; Jacobs & van Ingen Schenau, 1992; Johnson & Buckley, 2001; Hunter et al., 2004c; Bezodis et al., 2008; Charalambous et al., 2012), including a thigh, shank and foot segment. Although joint moments are generally calculated from distal to proximal joints (Winter, 2009), Bezodis et al. (2013) showed that the inclusion of MTP joint in the joint kinetic calculations had a negligible impact on the ankle, knee and hip joint moments. Bezodis et al. (2013) however reported that the end-point definitions of the segments play an important role in the calculations of joint powers and work at the ankle. A three segment model of the leg was shown to be sufficient to represent the joint kinetics of the ankle, knee and hip if the distal end-point of the foot is defined by the location of the MTP joint (Bezodis et al., 2013).

When performing an IAA, Chen (2005) and Patel et al. (2007) showed that the complexity of the kinematic model plays an important role in the outcome of an IAA. Chen (2006) reported the inclusion of distal degrees of freedom in the model had an important effect of the resulting contributions to CM accelerations. This suggests that the use of a three segment leg (i.e. one segment foot) versus four segment leg (i.e. two segment foot) will have an important effect on the results of an IAA and therefore needs to be considered. Similarly, Patel et al. (2007) reported some differences in the results relating to the contributions of the hip moment when comparing results between kinematic models that defined the pelvis and trunk as a single segment versus combining them as two separate segments. Patel et al. (2007) showed that the analysis using the combined pelvis and trunk segments underestimated the magnitudes of vertical accelerations induced on the upper body by the hip extensor moment. It is important that kinematic models should poses sufficient replicative validity to replicate the behaviour of the system being investigated (Zeigler, Kim & Praehofer, 2000). Ultimately, the complexity of the model used will be dependent on the aim of the research and the methods used to collect and process the data. As a rule, the models should be as simple as possible while being sufficient complexity to address the research questions (Yeadon & King, 2008).

# 2.4.4.2 Foot-floor contact models

The effects joint moments and forces have on the motion of multi-articulated body is influenced by the contact with the ground (Kuo, 2001). This is because the ground constrains the achievable motion of the system (Kuo, 2001). When preforming an IAA where the goal is to identify the accelerations induced on the CM during stance, the definition of how the foot interacts with the ground contact can have an important influence on the results (Dorn et al., 2010). In IAA literature involving a range of gait modalities (i.e. from walking to running and sprinting), ground contact models have generally involved rigid kinematic constraints applied at discrete points (e.g. Kepple et al., 1997; Hof & Otten, 2005; Hamner et al., 2010; Dorn et al., 2012; Cabral et. al., 2013; Koike & Nagai, 2016). These constraints ensure that accelerations at the contact points are zero (Heitmann, Ferns & Breakspear, 2012). The contributions to CM acceleration by a single joint moment therefore equals the acceleration needed to reduce the contact point acceleration to zero (Wang, 2012). In the literature, the number and location of these discrete points has varied between a single point located at the centre of pressure (e.g. Kepple et al., 1997; Hof & Otten, 2005; Cabral et al., 2013; Koike & Nagai, 2016) or multiple points located at various point across the sole of the foot (Lin, Kim and Pandy, 2011; Dorn et al., 2012).

The studies that have defined ground contact at a single discrete point during ground contact have generally also employed a single segment foot model (e.g. Kepple et al., 1997; Hof & Otten, 2005; Cabral et al., 2013; Koike & Nagai, 2016; Koike et al., 2017). These studies have generally modelled ground contact at the instantaneous COP. This could however lead to errors in IAA results due large fluctuations in the COP position relative to the foot (Koike et al., 2017). This could be especially problematic during initial contact when the GRFs are low (Smith et al., 2014). Studies that have used more complex foot models (e.g. multi-segment foot) have used multiple contact points have modelled the foot using multiple segments (e.g. Lin et al., 2011; Dorn et al., 2012; Koike, Ishikawa & Ae, 2010). Furthermore, Bezodis et al. (2015) found that when creating a simulation model of the first stance phase of sprinting, that a two-point contact model at the MTP and distal hallux

resulted in the most representative GRF data. Thus, while using only a single contact point might be sufficient when using a one-segment foot model, using multiple contact points to model ground contact may be necessary to model ground contact using multi-segment foot models. Finally, multiple contact points may also provide an effective method for reducing errors associated with COP fluctuations during ground contact (Koike et al., 2017). This may be especially problematic if the moment arm between the CM of the Foot and the COP is relatively small.

### 2.4.4.3 Inertia models

Knowledge of mass distributions, mass centres, and moments of inertia of segments are important aspects influencing kinematic and kinetic analyses in biomechanics (Winter, 2009). Body segment inertial properties (BSIP) define characteristics of the kinematic models used which are important inputs to IDA and IAA calculations. There are four methods are generally used to determine the BSIP. The first method involves ratio and regression equations based on the results from cadaver studies (e.g. Dempster, 1955; Clauser, McConville & Young, 1969; Chandler, Clauser, McConville, Reynolds & Young, 1975). These should however be taken with caution as it may be questionable to extrapolate the data to healthy athlete populations (Yeadon, 1990). The second method is based on mathematical models (e.g. Hanavan, 1964; Hatze, 1980; Yeadon, 1990) that determine the BSIP by approximating the body using geometric shapes (Robertson, 2014). This method has generally been shown to predict body mass to within 2.3% (Yeadon, 1990), yet they do however require specific measurements to be taken from the participants. The third method (e.g. Zatsiorsky & Seluyanov, 1983) is based on scanning and imaging techniques (e.g. Gamma-mass scanning) to estimate the BSIP. Although the equipment needed for these measurements are relatively expensive, Zatsiorsky and Seluyanov (1983) used this method to develop regression equations using data collected from an athletic population. This allows customised BSIP to be calculated for other participants. These data were later adjusted by de Leva (1996) to align with segment end-point definitions commonly used in biomechanics. The final method involves kinematic measures (e.g. kinematic measures of oscillating segments) to indirectly quantify BSIPs (Robertson, 2014). As this method generally requires the oscillating segments, it can only be used for distal segments (Robertson, 2014).

Ultimately, the choice of model will depend on various factors including the accuracy of the model, time to perform the necessary measurements and the characteristics of the participants to be investigated. The methods' ability to define the BSIPs of the body is important to many biomechanical investigations. Studies that have investigated the accuracy of different BSIP models have generally compared the calculated acceleration and CM location during free fall to gravitational acceleration and known CM locations. Bezodis (2006) compared the mathematical model of Yeadon (1990) to that of Zatsiorsky and Seluyanov (1983) and the adjusted model by de Leva (1996) for the calculation of gravitational acceleration and location of the CM during different body orientations during free fall. The author noted that although the differences between the methods were small, differences were more pronounced in movements associated with larger thigh ranges of motion. These may have been influenced by the differences in segmental mass distribution associated with the different models (Bezodis, 2006). Nonetheless, uncertainties associated with the inertial model used were previously found to be smaller than uncertainties associated with the kinematic data (Bezodis, 2006; Manning, 2014). Bezodis (2006) concluded that while all three methods could be used to determine the BSIP for trained athletes, using the adjusted Zatsiorsky and Seluyanov (1983) model provided by de Leva (1996) can provide a means to unobtrusively determine BSIP during testing sessions.

### 2.4.5 Statistical analysis approaches

## 2.4.5.1 Inferential statistics

Generally, making inferences about an effect involves significance testing of a null hypothesis (Mullineaux, 2007). This involves calculating the probability (p value) that the observed differences are representative of the true differences if the null-hypothesis were true (Vincent & Weir, 2012). However, while statistical significance testing of a null-hypothesis has traditionally been widely used in sport science research, the information gained merely provides a 'yes' or 'no' to the question of whether the observed differences were significant or not (Vincent & Weir, 2012; Winter, Abt & Nevill, 2014). Furthermore, null-hypothesis testing does not provide an indication of the magnitude of the effect, which is often what matters (Cohen, 1994). Confidence intervals can represent an alternative or addition to traditional null-hypothesis testing (Batterham & Hopkins, 2006; Vincent & Weir,

2012). A confidence interval represents the range within which the true population value is expected to fall (Batterham & Hopkins, 2006). When used in conjunction with null-hypothesis testing, confidence intervals can provide additional information about the size and direction (i.e. negative or positive) of the differences tested using null-hypothesis testing. When used on their own, confidence intervals can be used to makes inferences about the significance of differences by providing knowledge about whether the observed differences is significant (i.e. if the confidence interval of the difference does not cross zero) (Batterham & Hopkins, 2006). However, null-hypothesis testing, confidence intervals, or a combination of both, do not provide information about whether significant differences between two samples are important (Batterham & Hopkins, 2006). As Batterham & Hopkins (2006) warned, significant differences (as identified using either null-hypothesis testing or confidence intervals) can exist, but be too small to be considered important. This has clear implications for applied sport settings where coaches are often interested in the size of any differences or changes.

Magnitude based inferences (MBI; Batterham & Hopkins, 2006) offer an alternative method to make inferences about the mechanistic (i.e. positive, trivial or negative) or practical (i.e. harmful, trivial or beneficial) meaningfulness of an effect. With MBI, inferences about meaningful outcomes are based on probabilities that the true value is larger than a predefined smallest worthwhile change (SWC). When assessing the effectiveness of interventions, the SWC is generally variable dependent (Buchheit, 2016) and can be based on a subjective assessment of what would be considered the smallest change that is necessary for an intervention or differences between two samples to be considered a meaningful effect. However, this can often be difficult to determine, and therefore a smallest (standardised) effect of 0.2 is commonly adopted as the SWC (Winter et al., 2014). This means that a difference or change between two samples is only considered meaningful when it surpasses and effect size of 0.2. Furthermore, different magnitudes of effects can then be described in terms of Cohen's levels for effect sizes (e.g. small, moderate, large) to provide an enhanced level of interpretation of the mean effect (Batterham & Hopkins, 2006; Buchheit, 2016). MBI can also be used to describe the probabilities that the observed changes or differences are real (Batterham & Hopkins, 2006), where probabilities are presented using both qualitative (e.g. very likely) and quantitative (e.g. 90%) descriptors. These probabilities represent an assessment of the uncertainty of the observed effect and are assessed based on the confidence interval around the mean effect relative to the SWC.

# 2.4.6 Summary of methodological considerations

This review of the methodologies shows that there are a number of considerations necessary when selecting the appropriate means to collect data. Ultimately, while the choice of methods used to collect the data depend on the research questions to be addressed, it is important to ensure that the data obtained from the data collection methods are accurate. Furthermore, when processing the data, the different options available to reduce the noise in the data, and the kinematic and inertial models used to define the body of the participants need to be considered to ensure that valid results are obtained to address the specific research questions. Ultimately, the research questions, availability of facilities and equipment and sample population will influence the choice of methods used to address the aim of this thesis.

# 2.5 Chapter summary

The relevant literature relating to the biomechanics of sprinting was discussed. Furthermore, methods and equipment used to collect accurate data and the methods used to process the data were discussed. From the review of literature, the overall aim of the thesis: to understand biomechanical differences in technique between the initial acceleration, transition and maximal velocity phases of a sprint, was developed. Three key Themes were developed to address the aim of the thesis (Figure 1.1). The Themes and relevant research questions were address in three studies (Chapters 3 to 5).

The majority of research in sprinting has generally focused on understanding the mechanics of a single steps or phase in sprinting. However, less is known about the mechanical changes in the sprinters technique between different phases in sprinting. Since the acceleration phase in sprinting is key to the maximum velocity that a sprinter can achieve, a phase analysis (Theme 1) will provide an understanding of differences in the step-to-step changes in step characteristics and kinematics between the initial acceleration, transition and maximal velocity phases

in sprinting. This could ultimately provide a greater understanding of how variables that are more visually accessible (e.g. segment angles) changes during and between these phases.

The performance of sprinter throughout the initial acceleration, transition and maximal velocity phases is ultimately dependent on the work done by the muscles surrounding the joints of the stance leg. Theme 2 (Technique analysis) investigates the changes in joint kinematics and kinetics between the three phases. With previous research generally focussing on a singles step, there is still lack of understanding relating to the changes across different phases in maximal sprinting. Especially during sprint acceleration where running velocity increases step-to-step, knowledge of the changing joint kinetics can provide important information on the conditioning and technical needs of sprinters, which will undoubtedly aid coaches and sport scientists in the preparation of athletes for the sprint events.

The Induced acceleration analysis (Theme 3) will investigate contribution to CM acceleration due to different forces acting on the sprinters. Theme 3 will aim to build on the knowledge gained by Themes 1 and 2 by providing a better understanding of the influence that changes in kinematics and joint kinetics have on the performance of the sprinter. In the following chapters, empirical and theoretical analyses are presented to address the three research Themes of this thesis.

## Chapter 3 - Phase analysis: Phases in maximal sprinting

### **3.1 Introduction**

In a 100 m sprint, the maximum velocity athletes achieve is closely associated with the official race time (Moravec et al., 1988; Fuchs & Lames, 1990) and is dependent on their ability to accelerate (Morin, Edouard & Samozino, 2013). The acceleration phase is characterised by changes in body posture (Crick, 2013a; Nagahara, Matsubayashi et al., 2014), step characteristics, and contact and flight times (Čoh et al., 2006; Debaere, Jonkers & Delecluse, 2013; Nagahara, Naito, Morin & Zushi, 2014; Nagahara, Matsubayashi et al., 2014). The scientific and coaching literature have both proposed that the acceleration phase can be sub-divided into two phases (Delecluse et al., 1995; Seagrave, 1996; Crick, 2013a).

Different kinematic measures have previously been used to sub-divide the acceleration phase in sprinting. This was done by identifying breakpoint steps (i.e. a step where the step-to-step progressions of a measure shows a clear change) or a step when a measure crosses a pre-defined threshold or event. These steps were then used to sub-divide the acceleration phase into the initial acceleration and transition phases. The variables previously used include the height of the centre of mass (CM-h; Nagahara, Naito, Morin & Zushi, 2014), the intersection between contact and flight times (Coh et al., 2006) and the point when contact times start to plateau (Qing & Krüger, 1995). Coaching literature has proposed that the initial acceleration phase ends when the shank at touchdown becomes vertical, after which step-to-step changes in touchdown shank angles terminate (Crick, 2013e). Furthermore, the coaching literature suggests that the transition phase ends when step-to-step changes in the angle of the trunk at touchdown has terminated, after which sprinters are described as having an 'upright' posture (Crick, 2013f). This suggests that changes in the step-to-step progressions of shank and trunk angles could be adopted to sub-divide the acceleration phase. It is, however, unclear whether there is parity between the phases of sprint acceleration, which are identified using these different measures.

Throughout the acceleration phase in sprinting, step characteristics (Maćkala, 2007; Debaere, Jonkers & Delecluse, 2013; Nagahara, Naito, Morin & Zushi, 2014) and

kinematic variables change (Nagahara, Matsubayashi et al., 2014). While the horizontal velocity of a sprinter can be expressed in terms of step length and step frequency, the forces generated during ground contact ultimately determine an athlete's acceleration (Rabita et al., 2015). Since measuring forces may not always be practical in an applied setting, knowledge of how kinematic variables link to force application is important. One such variable is the angle between the vector connecting the centre of mass (CM) to the point of force application and the ground during ground contact (CM angle; di Prampero et al., 2005). The CM angle can be calculated from the vertical and anterior-posterior distances between CM and point of force application. Both of these have previously been shown to change during the acceleration phases (Nagahara et al., 204b). However, the multi-segment body means that the position of individual segments (e.g. shank, thigh and trunk position) influences the vertical and horizontal distances between the point of force application and the CM and therefore ultimately influences the CM angle. Since the CM angle is mechanically relevant to the acceleration performance of the athlete, knowledge of how the components of the CM angle during the phases of sprinting will be practically relevant to the understanding of the initial acceleration and transition phases in sprinting.

The aim of this chapter was to investigate differences in step-to-step changes in step characteristics and kinematic variables between the initial acceleration, transition and maximal velocity phases. To achieve this aim, the research question i - '*How comparable are the breakpoints separating the initial acceleration, transition and maximal velocity phases when identified using different measures?*' was addressed first. This will provide a better understanding of the appropriateness of measures previously used in research (e.g. CM-h or contact and flight times) to sub-divide the acceleration phase versus using shank and trunk angles which were identified from the coaching literature. Furthermore, this will provide the necessary data to objectively sub-divide the acceleration phase into the initial acceleration and transition phases and address research question ii - '*How do step-to-step changes of step characteristics and kinematics differ between the initial acceleration phase, transition phase and maximal velocity phase?*'. Such data would develop knowledge of the characteristics of the initial acceleration, transition and maximal velocity phases in sprinting.

Through a phase analysis of sprinting (Theme 1), the overall purpose of this chapter was to increase knowledge of the initial acceleration, transition and maximal velocity phases and assist with the development of technical models for different phases of sprinting. This will improve understanding of how variables that are more easily accessible to coaches and sport scientists in applied settings change within the phases of sprint acceleration.

# 3.2 Methods

### 3.2.1 Participants

To ensure that the identified sprint phases are representative across sprinters, male and female participants were recruited for this study. Five nationally competitive sprinters (Table 3.1) gave written informed consent to participate in the study after ethical approval was obtained from the university's Research Ethics Committee. The participants were injury free prior to and for the duration of data collection.

Table 3.1. Participant Characteristics.								
ID	Age	Gender	Height [m]	Body Mass [kg]	60 m/100 m PB [s]			
P01	27	Male	1.89	89.1	6.99/10.87			
P02	20	Male	1.79	73.5	6.80/10.64			
P03	19	Male	1.79	72.0	6.86/10.71			
P04	20	Female	1.76	69.4	7.65/12.34			
P05	25	Female	1.71	63.3	7.61/11.90			

Table 3.1. Participant Characteristics

# 3.2.2 Protocol

Data were collected on two separate days at the National Indoor Athletics Centre in Cardiff. The first data collection took place in March 2014 (which was after the participants had completed their indoor season). The second data collection was undertaken in May 2014 (eight weeks after the first session and early in the outdoor season). Immediately prior to the data collection, the participants' height and body mass were measured. For later inertial calculations, the mass of each participant's sprint shoes were measured using a standard (kitchen) scale (Salter, London). The participants were then instructed to complete their normal sprint specific warm-ups. Following their warm-up, each participant performed five maximal effort sprints over 50 m from starting blocks at each collection, with the exception of participant P03, who only completed three trials at the second data collection. Participants had a minimum of five minutes rest between each trial to ensure full recovery.

# 3.2.3 Data Collection

At both collections, five HDV digital cameras (camera 1: Sony Z5; cameras 2 and 3: Sony Z1; cameras 4 and 5: Sony A1E), each with a 12 m horizontal and 9 m vertical field of view, were set up 19 m from the running lane (Figure 3.1).



Figure 3.1. Camera and synch light set-up (not to scale). Direction of travel from left to right.

The cameras recorded in HD (1440  $\times$  1080) at 50 Hz with an open iris and a shutter speed of 1/600 s. There was a 2 m overlap between the cameras around the 10 m, 20 m, 30 m and 40 m marks. A sixth camera (Sony Z5) was set up perpendicular to the 25 m mark elevated 5 m above the track and 40 m away from the centre of the lane. This camera was used as a panning camera to identify touchdown and toe-off events. It recorded in HD (1440  $\times$  1080) at 200 Hz with an open iris and a shutter speed of 1/600 s.

To obtain the data required for calibration, a calibration pole with three spherical control points (diameter of 0.100 m) was moved sequentially through known positions throughout the field of view. The calibration videos from each day allowed a 10.000 m × 2.170 m plane to be calibrated for each camera, which when all cameras were combined allowed a  $50.000 \times 2.170$  m plane to be created. To assess the accuracy of reconstruction, a pole with six points of known location was placed and recorded at various points along the plane. Two sets of 20 sequentially

illuminating LEDs (Wee Beastie Electronics, Loughborough, Leicestershire, UK), which were visible in cameras 1 to 4, were used to identify the starting signal and synchronise the cameras. This allowed the cameras to be synchronised to the nearest 0.001 s (Irwin & Kerwin, 2006). The illumination of the lights was synchronised with an audible starting noise, which was used to start the participants.

## 3.2.4 Data Reduction

The videos were extracted from the camera tapes using Dartfish Team Pro 6.0 (Dartfish) and then converted to .avi format and de-interlaced in VLC 2.1.3 (VideoLan, France). The videos were then digitised in Matlab (The MathWorks Inc., USA, version R2014a) using an open source digitising package (DLTdv5.m, Hedrick, 2008, http://unc.edu/~thedrick/software1.html). Digitising was completed at a 2× zoom and quarter-pixel accuracy, providing a resolution of measurement of 0.002 m for the current analysis. To reconstruct the digitised coordinates, an open source 8 parameter 2D DLT camera calibration and point reconstruct code (Woltring & Huiskes, 1985; Meershoek, 1997; http://isbweb.org/software/) was edited to include a ninth parameter. The inclusion of the ninth parameter allowed for the correction of lens distortion (Walton, 1981).

The calibration data was acquired by digitising by the centroids of each of the spherical calibration points. This allowed the calculation of the nine DLT parameters needed to convert the digitised data from pixel coordinates to real world coordinates (i.e. meters). To determine the spatial reconstruction accuracy, the accuracy points which were included in the calibration videos were digitised and re-constructed. The accuracy of spatial data reconstruction was then assessed by calculating the horizontal and vertical RMSD between reconstructed and known locations.

Following visual identification, two frames around each touchdown (last frame before and first frame of ground contact; Bezodis, 2006) and toe-off (last frame before and first frame of flight) were digitised. Sixteen specific points were digitised: vertex and seventh cervical vertebra (C7), then both hips, shoulder, elbow, wrist, knee, ankle and MTP joint centres (Figure 3.2). A 17<sup>th</sup> point was included which was used to digitise the toe of the foot on the ground.



Figure 3.2. The 17 points digitised around touchdown and toe-off (see text for details).

Using the panning camera videos, touchdown and toe-off events were identified by marking the relevant frames using the DLTdv5 digitising package. Here, touchdown was defined as the first frame when the foot was visibly on the ground while toe-off was defined as the first frame when the foot was visibly in the air following stance. The process of identifying touchdown and toe-off was repeated three times with at least five days between repeat intervals. The touchdown and toe-off events identified consistently in at least two of the three repeats were used for further processing. The identified frames were processed in Matlab to calculate touchdown event times as well as contact time, flight time and step time.

# 3.2.5 Data synchronisation

Cameras 1 to 4 and the panning camera were synchronised using the synchronisation lights described in section 3.2.3. Camera 5 was subsequently synchronised to cameras 1 to 4 based on a calculated time offset, which was calculated from touchdown and toe-off data obtained from cameras 4 and 5. The time offset was calculated by estimating the CM position of the participant in camera 5 relative to participant's same position in camera 4.

Due to the limitation of 50 Hz video regarding temporal variables (Salo, Grimshaw & Marar, 1997) and since touchdown and toe-off events do not necessarily occur halfway between the two frames that were digitised around touchdown and toe-off, the event times from the panning camera were synchronised to each of the static cameras. This was done in one of two ways:

- The first method involved using the triggering of the LED synch lights, which triggered an event that was visible in cameras 1 to 4 and the panning camera.
- The second method was used when the triggering of the LED lights was not captured on the panning video. This method involved fitting the touchdown and toe-off events identified in the panning camera to those of the static cameras using a least squares approach.

After synchronising the 50 Hz data with the 200 Hz touchdown and toe-off data, the coordinate positions of each of the digitised points (excluding the toe point) at the touchdown and toe-off events were then calculated via linear interpolation between the two frames digitised around touchdown and toe-off using a custom written Matlab script.

# 3.2.7 Data Processing

After determining the coordinate positions at touchdown and toe-off, a custom written Matlab script was used to calculate the variables of interest. The whole-body CM was calculated based on the summation of the segmental moment approach (Winter, 2009). This was based on the inertia data from de Leva (1996) apart from the foot segment for which Winter's (2009) data were used with the added mass of each athlete's running shoe. The event times and corresponding horizontal and vertical CM (CM-h) locations, segment CM locations and joint centre locations were then used to calculate the following variables:

50 m times [s]: Time at 50 m minus reaction time. Reaction time was determined by identifying the first movement of the athlete in the blocks using the 200 Hz panning camera video. This data were used to identify each participant's quickest time at each data collection.

Step velocity  $[m \cdot s^{-1}]$ : The mean velocity during a step, calculated as the horizontal displacement of the CM between two consecutive touchdowns divided by the time between the touchdown events.

Step length [m]: The horizontal distance covered by the CM between two consecutive touchdowns (Nagahara, Matsubayashi et al., 2014).

Step frequency [Hz]: Defined as the rate at which steps were taken and was calculated as the inverse of step time (sum of contact and flight times) which was determined from the panning camera.

*Contact time* [*s*]: The duration the foot was in contact with the ground, calculated by subtracting the touchdown event time from the subsequent toe-off event time.

*Flight time [s]:* The duration between ground contacts, calculated by subtracting the toe-off event time from the subsequent touchdown event time.

Contact distance [m]: The horizontal distance the CM travelled during ground contact.

Flight distance [m]: The horizontal distance the CM travelled during the flight phase.

*Touchdown distance (TD<sub>distance</sub>) [m]:* The horizontal distance between the MTP marker and the CM at touchdown. Negative values indicate that the MTP marker was behind the CM at touchdown.

*Toe-off distance (TO<sub>distance</sub>) [m]:* The horizontal distance between the CM at toe-off and the average toe position during touchdown. Negative values indicate that the toe marker was behind the CM at toe-off.

Segment angles were calculated as the angle between the horizontal forward line and the vector created from the segment end-points using the inverse tangent. Trunk ( $\theta_{trunk}$ ), thigh ( $\theta_{thigh}$ ) and shank ( $\theta_{shank}$ ) angles at touchdown and toe-off were calculated. The touchdown and toe-off segment angles were then used to calculate the range of motion of the segments during ground contact.

Data from each camera were then combined to provide data for the full 50 m sprint trial. Only complete contact data (i.e. touchdown and toe-off data) that occurred

within the horizontal boundary of each individual camera was used. The 2 m overlap between the cameras ensured that at least one full set of contact data (i.e. touchdown and toe-off) was captured by at least one camera. Since all participants performed at least 25 steps within the 50 m sprint, the first 25 steps of each sprint were used for further analysis.

## 3.2.8 Identifying the initial acceleration, transition and maximal velocity phases

The phase identification was based on identifying the breakpoint step, which separated the initial acceleration phase from the transition phase ( $T_{start}$ ), and the breakpoint step, which separated the transition phase from the maximal velocity phase ( $MV_{start}$ ). The initial acceleration phase was therefore defined as starting with the first step of the sprint and ending with the step immediately before  $T_{start}$ . The transition phase was defined as starting at the step  $T_{start}$  and ending with the step before immediately before  $MV_{start}$ . The maximal velocity phase was defined as starting at the step  $T_{start}$  and ending with the step before immediately before  $MV_{start}$ . The maximal velocity phase was defined as starting from  $MV_{start}$  until step 25 (Figure 3.3).



**Figure 3.3.** Schematic representation of the sub-division of the acceleration phase. The black line represents the initial acceleration phase, the blue line represents the transition phase and the red line represents the maximal velocity phase.

 $T_{\text{start}}$  and  $MV_{\text{start}}$  breakpoint steps were identified using a range of different step-tostep measures previously used in scientific and coaching literature (Table 3.2).

Table 3.2. Measures used to sub-c	livide the accel	leration phase	in sprinting,	the event these
measures identify	y and the study	y that used the	measure.	

Measure	Event	Source
Step-to-step changes in CM-h	$T_{start}$ , $MV_{start}$	Nagahara, Matsubayashi et al., 2014
Step-to-step changes in shank angles	T <sub>start</sub>	Crick, 2013a
The step when the flight time equalled or exceeded the contact time (CT≤FT)	T <sub>start</sub>	Čoh et. al., 2006
Step-to-step changes in trunk angles	MV <sub>start</sub>	Crick, 2013a

 $T_{\text{start}}$ : The breakpoint step for the start of the transition phase (T<sub>start</sub>) was identified based on step-to-step increases in 1) touchdown CM-h and 2) touchdown shank angles ( $\theta_{\text{shank}}$ ). It was predicted based on previous literature (Nagahara,

Matsubayashi et al., 2014; Crick, 2013e; Delecluse et al., 1995) that T<sub>start</sub> would occur within the first 10 steps. Therefore, to remove the possible effect of the data towards the latter end of the 50 m, only the first 10 steps of the full 25 step data set was used. To identify this step, a method involving multiple straight-line approximation (Neder & Stein, 2006; Nagahara, Matsubayashi et al., 2014) was used. Firstly, step-to-step changes in CM-h and  $\theta_{shank}$  were approximated using multiple first order polynomials where the first approximation included the first three touchdowns, the second approximation included the first four touchdowns and so on. With each subsequent approximation the number of touchdowns used was increased by one until the first 10 touchdowns were included in the approximation. Then, for each approximation, a residual score was calculated based on the RMSD between the raw and approximated data points. The differences between the residuals of adjacent approximations were then calculated where the first difference of residuals corresponded to step three, the second difference of residuals to step four, and so on. Finally, T<sub>start</sub> was identified as the step corresponding to the maximal difference between the residuals. The method described above was used to detect T<sub>start</sub> from both CM-h and shank angles at touchdown (Figure 3.4).



**Figure 3.4.** Example detection of  $T_{start}$  using multiple first order polynomials. The open circles represent the relative CM-h at each touchdown. The red and black lines represents two of the eight first order polynomials used to detect  $T_{start}$ . The grey diamonds represent the difference between the residuals of adjacent approximations. The vertical dotted line indicates the step ( $T_{start}$ ) which corresponds to the maximal difference of the residuals.

A third measure was identified as a possible way to identify  $T_{start}$ . This measure was identified as the step when flight time equalled or exceeded contact time (CT $\leq$ FT) during the acceleration phase. This measure, which was previously used by Čoh et al. (2006) and will be compared to the  $T_{start}$  steps, which were identified using both the CM-h and shank angles.

*MV*<sub>start</sub>: The breakpoint step for the start of the maximal velocity phase (MV<sub>start</sub>) was identified based on step-to-step increases in 1) touchdown CM-h and 2) touchdown trunk angles ( $\theta_{trunk}$ ). Data from step eight onwards were used to detect this step. A method using two first order polynomials (Schneider, Phillips, & Stoffolano, 1993; Nagahara, Matsubayashi et al., 2014) was used to identify MV<sub>start</sub> as follows. Firstly, the data (steps 8 to 25) were divided into two sections (Nagahara, Matsubayashi et al., 2014). The first section included steps eight to ten while the second section included steps ten to 25. Then, a first order polynomial was fit to each of the sections and an overall RMSD residual between the raw data and the approximated data was calculated. The step linking the two sections (initially step 10) was then moved sequentially through the data set up to the third to last step (23<sup>rd</sup> touchdown). Each time the linking step was moved the new sections were approximated using two new first order polynomials and an overall RMSD residual between the raw data and the approximated data and was calculated for the new approximation. The linking step that corresponded to the minimum RMSD residual was adopted as MV<sub>start</sub>. The method described above was used to detect MV<sub>start</sub> using both CM-h and trunk angles at touchdown (Figure 3.5).



**Figure 3.5.** Example breakpoint detection of  $MV_{start}$  using two straight-line approximations. The open circles represent the relative CM-h at each touchdown. Relative CM-h was plotted against touchdown times. The two black lines on the figure represent the two first order polynomials to detect  $MV_{start}$ . The grey diamonds represent the collective RMSD for each set of approximations. The vertical dotted line indicates the step ( $MV_{start}$ ) which corresponds to the minimal difference of the residuals.

#### 3.2.9 Data smoothing

Following the identification of the  $T_{start}$  and  $MV_{start}$  the step-to-step data was then smoothed to remove the effects of any bilateral differences, as well as potential noise due to the data collection and processing procedures. Data were smoothed using the Hanning moving averages algorithm (Equation 3.1 ; Grimshaw, Fowler, Lees & Burden, 2004). This algorithm was selected as it places a greater weighting factor on the point being smoothed instead of a standard moving average algorithm were all the points have an equal weighting. It was assumed that the data was evenly spaced (i.e. step one, step two, step three etc.).

 $y_i = 0.25 * x_{i-1} + 0.5 * x_i + 0.25 * x_{i+1}; i = 2 to (N-1)$  [Equation 3.1]

$y_i$	= newly calculated 'smooth' value
$x_i$	= original data
i	= touchdown or toe-off point being smoothed
Ν	= number of steps

## 3.2.10 Reliability and Objectivity of digitising

To assess reliability and objectivity of digitising, two experienced digitisers each digitised one trial three times. Each re-digitisation included the identification of the touchdown and toe-off events in the panning videos and digitising two frames around touchdown and toe-off in the static videos. Data from this was then used to calculate the within-digitiser (reliability) and between-digitiser (objectivity) differences in the variables identified in section 3.2.5. These results are discussed in appendix A1.

## 3.2.11 Data Analysis

To address the first research question, which involves the measures used to identify the breakpoint during the acceleration phase in sprinting, all three to five trials from the participants from each day where used. All the trials were included to allow a more robust and thorough comparison of the different measures that are used to sub-divide the acceleration phase in sprinting. The mean and standard deviations (SD) of the detected T<sub>start</sub>, MV<sub>start</sub>, CT≤FT and the step at which the participants achieved their maximal step velocity (V<sub>max</sub>) was calculated across each participant and the group. Furthermore, a mean and SD of the relative CM-h (% of stature), shank angles ( $\theta_{shank}$ ), trunk angles ( $\theta_{trunk}$ ) and step velocities (absolute and relative to the maximal velocity) corresponding to the T<sub>start</sub>, MV<sub>start</sub>, CT≤FT and V<sub>max</sub> steps were calculated. The differences in the T<sub>start</sub> steps, which were identified using the measures CM-h, shank angles and CT≤FT, were quantified by calculating an individual and group RMSD between each of the measures for each day. The same was done to quantify the differences between the MV<sub>start</sub> steps which were identified using either CM-h or trunk angles.

To address the second research question, each participant's best trials from days one and two were selected for further analysis. This selection was based on the fastest 50 m sprint times. This allowed the investigation of the step-to-step changes in step characteristics and kinematics associated with the participant's best performance on each day. To identify the steps occurring in the initial acceleration, transition and maximal velocity phases, the range of  $T_{start}$  (CM-h) and MV<sub>start</sub> (CM-h) steps identified from those best trials was used to sub-divide the trials. Finally, the smoothed step characteristic, spatiotemporal and kinematic data of each participant's best trial on each day was presented to investigate the differences between the initial acceleration, transition and maximal velocity phases. Step-to-step changes in the variables during the initial acceleration, transition and maximal velocity phases were qualitatively described as showing a steep rise (or decline), a less step rise (or decline) or plateau. A plateau is defined as a period of unclear step-to-step increases or decreases in a variable.

# 3.3 Results

Reconstruction errors ranged from 0.003 to 0.005 m horizontally and 0.002 to 0.004 m vertically. The within-digitiser differences for the step characteristics (step velocity, step length) were below 1% of their respective range across the first 25 steps while the between digitiser differences were 0.033 m for step length and 0.07 Hz for step frequency. Within and between digitiser differences for segment angles were  $\leq 3^{\circ}$  or 4% of the variable's respective range. Within and between digitiser uncertainties for CM-h were below  $\leq 0.5\%$  of stature or 5% of the variable's range over the first 25 steps of the sprint. Within-digitiser uncertainties in contact distances were 0.010 m or 4% of the variables range while between-digitiser differences in contact distances were 0.035 m or 13% of the range. The larger between digitiser differences for step length, step frequency and contact distances were due to the between-digitiser differences in touchdown and toe-off events. Touchdown and toe-off events were identified to the same frame 67% of the time, with one frame difference (0.005 s) 31% of the time and with a two frame difference (0.010 s) 2%

of the time. See Appendix A1 for a more complete discussion of reliability and objectivity results.

# 3.3.1 Trial times, T<sub>start</sub>, MV<sub>start</sub> and CT≤FT

Participant P02, who at the time of testing had the best 100 m personal best of the male participants, ran the fastest 50 m overall on day 1 with a time of 5.86 s (Table 3.3). Out of the two female participants, P05 ran the fastest 50 m on both days with 6.63 s and 6.75 s on days 1 and 2, respectively (Table 3.3). Only participant P01 improved on their best performance from day 1 to day 2 (6.13 to 6.07 s).

collection as well as each participant's range across the thats.							
	Day 1	Day 2					
Participants	Range [s]	Range [s]					
P01	6.13 – 6.21	6.07 - 6.15					
P02	5.86 - 5.94	5.98 - 6.01					
P03	5.90 - 5.96	5.89 - 5.94					
P04	6.78 – 6.90	6.83 - 7.06					
P05	6.63 – 6.75	6.75 – 6.78					

**Table 3.3.** Mean  $(\bar{x}) \pm SD$  50 m time from the March and May 2014 data collection as well as each participant's range across the trials.

Ranges of T<sub>start</sub> steps identified using either CM-h or shank angles were consistent between the two days (Table 3.4). Across both days, T<sub>start</sub> was detected between steps 3 - 7 when using touchdown CM-h and between steps 3 - 6 when using touchdown shank angles (Table 3.4). The shank reached a 90  $\pm$  2° touchdown position between steps 5 - 15. For the individual data for each participant, see Appendix A2.

**Table 3.4.** Group mean  $(\bar{x}) \pm SD$  using all available trials, ranges across all trials and ranges across the best trials for T<sub>start</sub> steps (CM-h, shank angles ( $\theta_{shank}$ ) and CT≤FT) and MV<sub>start</sub> steps (CM-h and trunk angles ( $\theta_{trunk}$ )). Also presented are the CM height,  $\theta_{shank}$  and  $\theta_{trunk}$  at their respective T<sub>start</sub> and

MV start Steps.										
T <sub>start</sub>							MV <sub>start</sub>			
	CM-h			θ <sub>shank</sub> CT		CT≤FT	CM-h		$\theta_{trunk}$	
	Day	Step	Height	Step	Angle	Step	Step	Height	Step	Angle
			[%]		[°]			[%]		[°]
$\bar{x} \pm SD$	1	4.5 ±1.3	51 ±1	4.8 ±1.0	78 ±8	13.2±2.4	15.0 ±1.2	56 ±1	16.0 ±1.4	82 ±4
(all trials)	2	4.7 ±1.0	51 ±1	4.7 ±1.0	76 ±5	11.5±1.6	14.8 ±1.5	56 ±1	15.2 ±1.5	82 ±3
Range	1	3 - 7	48 -53	3 - 6	57-90	9 -16	12 - 17	54-57	13 - 18	75-88
(all trials)	2	3 - 7	49 -53	3 - 6	65-85	8 -15	13 - 17	54-57	12 - 19	77-86
Range	1	4 - 6	49 -52	4 - 6	69-85	9 -16	14 - 16	55-56	14 - 17	75-88
(Best trials)	2	4 - 6	51 -53	4 - 6	67-85	10 -15	14 - 17	55-56	15 - 17	79-86

The range of CT≤FT steps was smaller on day two and generally occurred earlier across all participants (Table 3.4). Across both days, the maximal step velocity was

reached between steps 18 to 25 where the participants achieved 8.56 - 10.76 m  $\cdot$ s<sup>-1</sup> (Table 3.5).

			V <sub>max</sub>		
	Day	Step	SV [m⋅s⁻¹]	CM-h [%]	θ <sub>trunk</sub> [°]
x̄±SD	1	23.3 ± 2.1	9.81 ± 0.74	56 ± 1	84 ± 3
(all trials)	2	22.9 ± 1.4	9.74 ± 0.74	56 ± 1	84 ± 2
Range	1	18 - 25	8.83 - 10.76	53 - 58	79 - 89
(all trials)	2	19 - 25	8.56 - 10.63	54 - 57	81 - 90
Range	1	23 - 25	9.04 - 10.73	55 - 57	79 - 87
(Best trials)	2	22 - 24	8.86 - 10.63	55 - 57	82 - 90

**Table 3.5.** Group mean  $(\bar{x}) \pm SD$  of  $V_{max}$  steps as well as the ranges (all trials and best trials) for  $V_{max}$  steps. Group mean  $(\bar{x}) \pm SD$  and ranges (all trials and best trials) of step velocity (SV), CM-h and trunk angle ( $\theta_{trunk}$ ) corresponding to the  $V_{max}$  step are also

To make the comparison between  $T_{start}$  and  $MV_{start}$  steps identified using different measures more robust, all trials were included in this analysis. The RMSD between  $T_{start}$  steps identified using either CM-h or shank angles, ranged between 0.8 – 2.1 steps (Table 3.6). The RMSD between  $T_{start}$  steps identified using the CT≤FT step or either CM-h and shank angles ranged from 5.9 - 12.2 steps. The RMSD between  $MV_{start}$  steps identified using CM-h or trunk angles were between 1.3 - 2.3 steps (Table 3.6).

Table 3.6. Individual RMSD between T<sub>start</sub> steps identified either using CM-h, shank angles or the CT≤FT step and the RMSD between MV<sub>start</sub> steps identified using either CM-h or trunk angles. These RMSD values were calculated using all trials for each participant.

				•	
			T <sub>start</sub>		MV <sub>start</sub>
Participant	Day	CM-h vs. θ <sub>shank</sub>	CM-h vs. CT≤FT	θ <sub>shank</sub> vs. CT≤FT	CM-h vs.  trunk
D04	1	1.6	8.0	9.4	1.3
FUI	2	1.5	7.9	7.2	1.4
P02	1	1.2	6.0	5.7	1.6
	2	0.8	6.4	6.2	2.0
P03	1	2.1	12.2	10.7	2.3
	2	1.3	7.7	7.4	1.3
P04	1	1.1	10.1	9.3	1.6
	2	1.1	7.6	8.3	1.7
P05	1	1.1	8.3	7.8	2.0
	2	0.9	5.9	6.5	1.7

CM-h: centre of mass height (%);  $\theta_{shank}$ : shank angle (°);  $\theta_{trunk}$ : trunk angle (°); CT $\leq$ FT: flight time exceeds contact time

# 3.3.3 Changes in step characteristics, spatiotemporal and kinematic variables

To investigate the step characteristics and kinematics associated with the participant's best performance on each day, only data from each participant's best trial based on the 50 m times was used. After identifying the best trials, the ranges

of  $T_{\text{start}}$  and  $MV_{\text{start}}$  steps from those trials were used to sub-divide the whole 50 m sprint trial into three phases (shaded areas; Figure 3.6).



**Figure 3.6.**  $T_{start}$  and  $MV_{start}$  steps of the participant's best trial from day 1 (**x**) and day 2 (+). The grey columns highlight the initial acceleration, transition and maximal velocity phase steps that lie outside the range (best trials) of  $T_{start}$  and  $MV_{start}$  steps.

Steps one to three were always part of the initial acceleration phase, steps six to 13 were always within the transition phase and steps 17 onwards always fell into the maximal velocity phase. When using each participant's best trial from each day,  $T_{start}$  using CM-h was associated with step velocities of 6.06 to 7.83 m·s<sup>-1</sup> or 65 to 77 % of V<sub>max</sub>, while MV<sub>start</sub> was associated with step velocities of 8.19 to 10.07 m·s<sup>-1</sup> or 92 to 98% of V<sub>max</sub>. Over the 25 steps, the largest changes in step characteristics (Figure 3.7) occurred during the initial acceleration phase (i.e. steps 1 to 3).

During the initial acceleration phase, step velocity, step length and step frequency showed a steep increase (Figure 3.7), while during the transition phase, the step velocity and step length curves became less steep showing that step-to-step increases continued at a slower rate relative to the initial acceleration phase. The maximal velocity phase was characterised by small step-to-step increases in step velocity and step length.



**Figure 3.7.** Step-to-step profiles for (a) step velocity, (b) step length and (c) step frequency over the first 25 steps of the participants best 50 m sprint from day 1 (black) and day 2 (grey). The grey columns highlight the initial acceleration, transition and maximal velocity phase steps that lie outside the range (best trials) of  $T_{start}$  and  $MV_{start}$  steps.

Figure 3.8 shows the step-to-step pattern of CM-h and step-to-step changes of CM-h. The initial acceleration phase was characterised by a steep rise in the height

of the CM. During the transition phase, the CM-h curve became less steep, characterised by a step-to-step CM-h changes between 0.0 -1.0% of stature.



**Figure 3.8.** a) Touchdown CM-h and b) step-to-step changes in CM-h step over the first 25 steps of the participants best 50 m sprint from day 1 (black) and day 2 (grey). The grey columns highlight the initial acceleration, transition and maximal velocity phase steps that lie outside the range (best trials) of T<sub>start</sub> and MV<sub>start</sub> steps.

The initial acceleration phase was characterised by a steep rise in flight time, contact distance, flight distance and touchdown distance while contact times showed a steep decline (Figure 3.9). During the transition phase, the flight time and contact time curves became less steep showing a decrease in the magnitude of step-to-step changes. In addition, during the transition phase, the contact distance curves started to plateau. This was associated with a slowing down of the step-to-step increases in touchdown distance when compared with the initial acceleration phase. Throughout the initial acceleration and transition phases, flight distance and toe-off distances showed relatively consistent step-to-step changes. During the maximal velocity phase, contact times, contact distances, touchdown and toe-off distances had plateaued while flight time and flight distance continued to show small step-to-step increases.



**Figure 3.9.** Step-to-step contact times (a), flight times (b), contact distance (c), flight distance (d), touchdown distance (e) and toe-off distances profile over 25 steps of the participants best 50 m sprint from day 1 (black) and day 2 (grey). Grey columns highlight the initial acceleration, transition and maximal velocity phase steps that lie outside the range (best trials) of T<sub>start</sub> and MV<sub>start</sub> steps.

The touchdown angle and range of motion of the shank (Figure 3.10 g & i) showed a steep step-to-step increase during the initial acceleration phase. During the transition phase, shank angles showed a less steep step-to-step increase before reaching a plateau during the maximal velocity phase. Touchdown angle and range of motion of the thigh (Figure 3.10 d & f) increased early in the initial acceleration phase, and then decreased during the transition phase before plateauing during the maximal velocity phase. Trunk angles at touchdown and toe-off increased throughout the initial acceleration and transition phases (Figure 3.10 a & b).


**Figure 3.10.** Step-to-step trunk (a-c), thigh (d-f) and shank (g–i) angle and ranges of motion profiles over the first 25 steps of the participants best 50 m sprint from day 1 (black) and day 2 (grey). The grey columns highlight the initial acceleration, transition and maximal velocity phase steps that lie outside the range (best trials) of T<sub>start</sub> and MV<sub>start</sub> steps.

## 3.4 Discussion

The angle between the vector connecting the CM to the contact point and the ground is mechanically relevant to the acceleration performance of the athlete (di Prampero et al., 2005). However, knowledge of how the components of the CM angle (e.g. TD distance, TO distance, segment angles) change during sprinting is still unclear. Based on Theme 1 (Phase analysis), the aim of this chapter was to investigate differences in step-to-step changes in step characteristics and kinematic variables between the initial acceleration, transition and maximal velocity phases. The purpose was to increase knowledge of the initial acceleration, transition and maximal velocity phases and assist with the development of technical models for different phases of sprinting. To achieve this, two research questions were posed. The first research question posed in the introduction of this chapter asked how comparable the breakpoint step (T<sub>start</sub>) which links the initial acceleration to the transition phase and the breakpoint step (MV<sub>start</sub>) which links the transition to the maximal velocity phase are when identified using different measures (section 3.4.1). This ultimately informed the choice of measure, which was used to sub-divide the whole 50 m sprint into the initial acceleration, transition and maximal velocity phases and address research question ii concerning the step-to-step changes in step characteristics and kinematic variables between the initial acceleration, transition and maximal velocity phases (section 3.4.2).

#### 3.4.1 Comparison of measures used to identify the acceleration phases

Before sub-dividing the acceleration phase in sprinting, an analysis of measures previously used to achieve this was necessary. To allow a more robust comparison between the measures used previously to identify the breakpoint during the acceleration phase in sprinting, all available trials were used to address the first research question of Theme 1. Using the CM-h at touchdown as the discriminating measure to identify  $T_{start}$  and  $MV_{start}$ , the range of breakpoint steps for  $T_{start}$  were steps 3 to 7 and for  $MV_{start}$  steps 12 to 17. While the current study used CM-h at touchdown, a previous study Nagahara, Matsubayashi et al. (2014) used the mean CM-h during stance as their measure to sub divide the acceleration phase in sprinting. Nonetheless, similar ranges of  $T_{start}$  and  $MV_{start}$  steps were identified in the current study compared to those of Nagahara, Matsubayashi et al. (2014) who identified  $T_{start}$  between steps 3 to 6 and  $MV_{start}$  between steps 10 to 20. The current

study showed the consistency of  $T_{\text{start}}$  and  $MV_{\text{start}}$  between separate data collection days, which further verifies the location of these events.

Using shank angles,  $T_{start}$  was identified between steps 3 to 6. These results show parity with the model presented by Crick (2013e) which proposes that the initial acceleration phase lasts around 5-7 steps after which the shank is perpendicular to the ground at touchdown. In this study,  $T_{start}$  was associated with shank angles ranging from 57° to 90°. This is different to the ~90° shank angle suggested by the British Athletics coaching literature (Crick, 2013e). In the current study 90 ± 2° degrees was only reached between steps 5 to 15. The 90 ± 2° threshold was used as this incorporates the potential uncertainty of shank angles identified from the reliability and objectivity analysis. As shown in figure 3.10g, shank angles do not progress in a linear fashion until vertical as suggested by the British Athletics coaching literature (Crick, 2013e). Using a vertical threshold to identify  $T_{start}$  may therefore not be appropriate to identify abrupt changes in the step-to-step progression of this variable.

Following the transition phase, an 'upright' trunk is characteristic of the maximal velocity phase and therefore the plateau in step-to-step changes in trunk angle at touchdown could serve as a measure to detect this event (Crick, 2013e). According to the British Athletics sprint model, this is suggested to occur around step 17 (Crick, 2013e). In the current study steps 12 - 19 were identified as the steps trunk angle plateaued and therefore participants started their maximal velocity phase. Although 'upright' was not defined in previous literature, in this study step-to-step changes in trunk angles plateaued at trunk angles of 75° to 88°.

The CM-h at each step is determined by the segment orientations, where a vertical orientation of the segments provide maximal contribution to CM-h. Since touchdown shank and trunk angles show the largest step-to-step changes during the initial acceleration and transition phases (Figure 3.10 a & g), increases in CM-h during the initial acceleration and transition phases could be expected to align with the step-to-step changes in both shank and trunk angles. In order to compare  $T_{start}$  and  $MV_{start}$  steps identified using the different measures an RMSD between the different steps was calculated.  $T_{start}$  based on CM-h and  $T_{start}$  using shank angles was

detected to within 2.1 steps of each other (Table 3.6). Similarly, MV<sub>start</sub> based on CM-h and MV<sub>start</sub> based on trunk angles was detected to within 2.3 steps of each other. Although relatively low, these RMSD step differences are possibly due to other segments (e.g. segments other than the shank and trunk) changing independently of each other and therefore influencing the CM-h. Furthermore, bilateral differences, which have previously been reported in maximal sprinting (Exell, Gittoes, Irwin & Kerwin, 2012) could have contributed to these RMSD step differences. While the within-trial analysis revealed that different T<sub>start</sub> and MV<sub>start</sub> steps were identified when using either CM-h or segment angles, both measures did provide similar ranges of T<sub>start</sub> and MV<sub>start</sub> steps across multiple trials. Therefore, using segment angles in applied settings, where speed of feedback is often an important factor may be an appropriate substitute if data are based on multiple trials (at least three trials per participant). However, since CM-h provides a holistic measure that is representative of the overall postural changes, this measure was subsequently used for identifying T<sub>start</sub> and MV<sub>start</sub> steps to address research question 2.

When using the step in which flight times were equal to or exceeded contact times (CT≤FT), steps 8 - 16 were identified as T<sub>start</sub>. Čoh et al. (2006) identified steps 8 - 10 as the start of the transition phase within one sprinter. The range of CT≤FT identified in the current study suggests that the location of this step can be inconsistent between participants and within participants across different days. Hunter et al. (2004) reported that running velocity and vertical impulse play an important part in contact and flight times. CT≤FT may therefore be dependent on running velocity and ability to generate large vertical GRF during ground contact. The RMSD between CT≤FT and  $T_{start}$  from CM-h and shank angles showed differences between 5.7 - 12.2 steps. While CT≤FT may represent a beneficial tool to monitor sprinters, this measure appears to be dependent on the sprinters' running velocity and ability to generate vertical impulses during short ground contacts and is not necessarily representative of changes in kinematics.

The characteristics of the breakpoints ( $T_{start}$  and  $MV_{start}$ ) that sub-divide the acceleration phase in sprinting is still a relatively unknown area in research. While  $T_{start}$  and  $MV_{start}$  steps were detected in the current study, it is unclear whether these

breakpoints are characteristic of the acceleration phase or a reflection of the method used to detect the steps (Ettema, McGhie, Danielsen, Sandbank & Haugen, 2016). Ettema et al. (2016) suggested that the T<sub>start</sub> steps identified by Nagahara, Matsubayashi et al. (2014), and therefore in the current study may be influenced by the method used to identify the breakpoint. Although Ettema et al. (2016) identified a T<sub>start</sub> breakpoint in some of their trials this was not the norm. It is important to note that Ettema et al. (2016) applied various fitting procedures including an exponential and piecewise fitting procedure. Only when the piecewise fit provided a greater goodness-of-fit did the authors conclude that a breakpoint occurred. Ettema et al., (2016) concluded that since T<sub>start</sub> was only identified in a minority of their trials, that this breakpoint might be reflective of an imperfection in performance. However, the authors did not relate the trials showing a T<sub>start</sub> breakpoint to performance, and therefore it cannot be clearly said that trials showing this breakpoint represent an imperfection in performance.

While the current study assumes that breakpoints occur in sprinting, this assumption is based on changes in posture, which have previously been reported in the acceleration and maximal velocity phases of sprinting (Delecluse, 1997; Nagahara, Matsubayashi et al., 2014; Crick, 2013a). In addition, apart from the current study, two other studies have identified a T<sub>start</sub> step (Nagahara, Matsubayashi et al., 2014; Ettema et al., 2016) in at least some of their sprint trials, which further justifies the approach of identifying breakpoint steps to sub-divide the acceleration phase in sprinting.

# 3.4.2 Changes in step characteristics, spatiotemporal and kinematic variables

For the remainder of this chapter, CM-h was adopted as the criterion measure to identify the  $T_{start}$  and  $MV_{start}$  breakpoint steps used to sub-divide the acceleration phase in sprinting. Because the best trials are more representative of optimal performance throughout the phases, the range in  $T_{start}$  and  $MV_{start}$  steps identified using the best day one and day two trials were used for each participant. This allowed the identification of the steps that occurred in the initial acceleration, transition and maximal velocity phases across all participants. These trials were then also used to investigate the step-to-step differences in step characteristics, spatial-temporal variables and segment kinematics between the initial acceleration,

transition and maximal velocity phases. The purpose was to clarify changes between the initial acceleration, transition and maximal velocity phases in variables visually accessible to coaches and sport scientists in an applied setting.

During the initial acceleration phase (steps 1 - 3), step characteristics (Figure 3.7), spatial-temporal variables (Figure 3.9) and segment orientations at touchdown and toe-off (Figure 3.10) all showed relatively large step-to-step changes compared with the transition and maximal velocity phases. During the initial acceleration phase, relatively large step-to-step increases in step velocity were due to large step-to-step increases in step length and step frequency (Figure 3.7). It must be noted that on the second day of testing, P02 (Figure 3.8c, grey dotted line) achieved a relatively high step frequency from the first step onwards. This was likely due to them having a relatively shorter contact time and contact distance over steps 1 and 2. Achieving a relatively high step frequency during the initial acceleration phase has been shown to be important to CM acceleration over the first three steps of a sprint (Nagahara, Naito, Morin & Zushi, 2014). In the current study, relatively larger step-to-step increases in step frequency during the initial acceleration phase resulted from larger step-to-step decreases in contact time relative to the step-to-step increases in flight times (Figure 3.9 a & b) therefore resulting in an overall shorter step time. While these characteristic increases in step frequency may also be present during slower sprints, running performance may ultimately be influenced by the ability to generate an overall larger step frequency (Hunter et al., 2004; Nagahara, Mizutani, Matsuo, Kanehisa & Fukunaga 2017b). Since sprinters can only alter their running velocity during ground contact, these results combined with those of Nagahara et al. (2014a) suggest an approach that allows a rapid increase in step frequency while still maximising contact time and therefore the contact distance should be encouraged. This may be achieved by minimising flight times and keeping the swing leg foot close to the ground during the recovery phase (Crick, 2013e).

Other step-to-step increases associated with the initial acceleration phase are relatively large step-to-step increases in contact and flight distances (Figure 3.9 c & d), touchdown distance (Figure 3.9 e) and trunk and shank angles at touchdown (Figure 3.10 a & g). Step-to-step increases in contact distance (Figure 3.9c) occurred mainly due to relatively large step-to-step increases in touchdown distance

(Figure 3.9e). The step-to-step increases in touchdown distance have previously been attributed to an inability to produce sufficient propulsive impulses to counteract the clockwise moment about the contact point due to gravity (Nagahara, Matsubayashi et al., 2014). The increases in touchdown distance which resulted from the relatively large step-to-step increases in shank angles (i.e. shank becoming more inclined; Figure 3.10g) and trunk angles (Figure 3.10a) likely play an important functional role in the performance during the acceleration phase. The magnitude of vertical force during short ground contacts has previously been suggested to be a limiting factor to maximising running velocities during maximum velocity steady state running (Weyand et al., 2000). Similar, the relatively large step-to-step increases in touchdown shank angles during the initial acceleration phase could be due to an increasing demand to generate vertical GRFs during initial ground contact to support step-to-step increases in CM-h and flight times as contact time's decrease (Crick, 2013e). Furthermore, step-to-step increases in flight times (Figure 3.9 b) would result in larger downward CM velocities immediately prior to touchdown. This would require larger vertical forces early during stance to slow the downward velocity of the CM.

From a mechanical perspective, an increased touchdown distance (i.e. more forward contact point relative to the CM) would alter the orientation of the GRF vector passing close to the CM, therefore ensuring a more inclined resultant GRF vector. Furthermore, it could be speculated that apart from influencing the touchdown distance, the more inclined shank could assist the sprinter in generating larger vertical forces by placing the sprinter in a better position to allow the hip extensors and ankle plantar flexors to apply force more vertically.

The increasing touchdown distances resulting from the step-to-step increases in touchdown shank (~7 to 12° per step) and trunk angles (~2 to 9° per step) could also influence the anterior force production of sprinters by influencing their whole-body orientation during subsequent steps. British Athletics coaching literature suggested that the smaller shank angles (<90°) during the initial acceleration phase are more favourable to generating large propulsive forces and should increase smoothly at around 6 to 8° between successive touchdowns, with sudden large increases thought to negatively affect the ability to generate large anterior forces

(Crick, 2013e). Indeed, a sudden large increase in touchdown shank angle could result in a large increase in touchdown distance, and therefore large increases in braking forces. Previous literature has shown that smaller touchdown distances are linked to smaller braking forces (Hunter, Marshall & McNair, 2005) and that a decreased touchdown distance is beneficial to performance during the first step of a sprint (Bezodis, Trewartha & Salo, 2015). Furthermore, since propulsive forces are important to performance during initial acceleration (Morin et al., 2015; Nagahara et al., 2017a), excessively large step-to-step increases in touchdown distances and segment angles may play a role in influencing the toe-off position sprinter achieve and therefore the propulsive forces sprinters could theoretically generate. Smaller step-to-step increases in touchdown shank and trunk angles may therefore be beneficial to performance by minimising the step-to-step increases in braking forces and placing sprinters in a better position to generate large propulsive forces as they approach toe-off.

Step-to-step changes in toe-off distances (range: -0.022 to 0.057 m per step) were relatively small compared to the step-to-step increases in touchdown distances (range: 0.020 – 0.148 m per step; Figure 3.10g). Kugler and Janshen (2010) have previously shown that faster participants achieved smaller CM angles and therefore larger propulsive forces than slower participants did. A larger toe-off distance and smaller CM-h will ensure a larger proportion of ground contact is spent with more forward orientated CM angle (see Appendix A3) and therefore according to the link between CM angle and acceleration (di Prampero et al., 2005) a forward orientated ground reaction vector. When comparing the initial acceleration to the transition phase, minimising the decreases in toe-off distances and increase in CM-h might be an essential characteristic of the initial acceleration phase that ensures that larger propulsive forces are generated when compared with the transition phase.

At the start of the transition phase ( $T_{start}$ ), the participants had reached 65% to 77% of  $V_{max}$  (6.06 to 7.83 m·s<sup>-1</sup>). The British Athletics performance model for sprinting (Crick, 2013g) suggests that sprinters should have reached around 75 - 80% of  $V_{max}$  at the start of their transition phase. The smaller percentages reported in this study may be because the transition phase was identified earlier (i.e. between steps 4-6) than suggested by the coaching literature (i.e. between steps 5-7; Crick, 2013e).

Steps six to 13 always occurred in the transition phase. During the transition phase, the curves associated with step frequency (Figure 3.8c), contact times (Figure 3.9a), flight times (Figure 3.9b) and touchdown shank angles (Figure 3.10g) were visibly less steep than during the initial acceleration phase. The transition phase was therefore characterised by relatively smaller step-to-step changes in the touchdown variables compared to the initial acceleration phase whereas trunk angles (Figure 3.10 a & b) continued to increase at a similar rate compared to the initial acceleration phase. This ensured that CM-h at touchdown also continued to increase throughout the transition phase.

Also during the transition phase, the participants' contact distances plateaued as the step-to-step increases in touchdown distance were matched by the step-to-step decreases in toe-off distances (Figure 3.9 e & f). The increasing flight times might play a role with the reduction of the step-to-step increases in touchdown distances by allowing the sprinters more time to actively swing the stance leg back relative to the CM prior to touchdown. This could also allow the sprinters to generate a larger downward velocity of the foot prior to touchdown, which plays an important role in generating vertical impulse directly after touchdown (Clark & Weyand, 2014). It is however unclear how the downward velocity of the foot relative to the CM changes between the initial acceleration, transition and maximal velocity phases and further exploration of this variable is needed. At toe-off, the decreasing toe-off distances are likely due to increasing trunk angles. This means that the hip joint reached full extension with the thigh less rotated forward (Figure 3.10e) with each consecutive step, thus resulting in a decreased toe-off distance. Although not directly measured, this data also suggests that hip joint range of motion decreases during the transition phase. This may be an important factor discriminating the initial acceleration phase from the transition and maximal velocity phases especially when considering specific training drills for the individual phases.

Step velocity and step length continued to increase during the transition phase, however at a relatively smaller rate than during initial acceleration phase (Figure 3.7). The step frequency curve plateaued during this phase compared with the initial acceleration phase as contact and flight times changed by comparable amounts in each step. This finding aligns with previous reports by Debaere, Jonkers &

Delecluse (2013) and Nagahara, Matsubayashi et al. (2014) that step frequency has already reached a near maximal level by step three. Nagahara et al. (2014a) reported that changes in step length are associated with changes in running velocity during the transition phase. As contact distance plateaued during the transition phase (Figure 3.9c), step lengths were further increased through increases in flight distance (Figure 3.9d). Increased flight times through increased vertical force generation may play an important role with further increases in flight distance as contact times decrease. The more inclined shank and trunk segments during the transition phase could aid further increases in flight times and decreases in contact times by allowing sprinters to generate a more vertically orientated GRF vector during ground contact.

At the start of the maximal velocity phase (MV<sub>start</sub>), participants had reached 92% to 98% (8.19 m·s<sup>-1</sup> to 10.07 m·s<sup>-1</sup>) of V<sub>max</sub>. The British Athletics performance model for sprinting (Crick, 2013g) suggests that sprinters will have reached 95% of their maximal velocity at the start of the maximal velocity phase. Steps 17 onwards always occurred in the maximal velocity phase. During the maximal velocity phase, step-to-step changes in spatial-temporal and kinematic variables started to plateau while small step-to-step increases in step velocity and step length occurred during this phase. These were due to small increases in flight distances while contact distances plateaued. Furthermore, the plateau in step-to-step changes in CM-h (Figure 3.8) and trunk angles (Figure 3.10a) meant that participants had reached their 'upright' running posture, which has been suggested to indicate the start of the maximal velocity phase (Crick, 2013f).

An 'upright' trunk represents an essential characteristic of the maximal velocity phase in sprinting. Firstly, a more inclined trunk could aid the sprinter in creating sufficiently large vertical forces (Clark & Weyand, 2014; Nagahara, Matsubayashi et al., 2014) which are important to maximise running velocities (Weyand et al., 2000). Secondly, an upright trunk would increase the tension in the hip flexors therefore allowing a quicker recovery following toe-off (Nagahara, Matsubayashi et al., 2014; Nagahara, Matsubayashi, Matsuo & Zushi, 2017) and allow sprinters to achieve a higher knee lift of the swing leg which would provide a greater distance to accelerate the foot back and down towards the ground (Morin et al., 2015). There is

however, still a lack of evidence that minimising the forward velocity of the foot during the late swing phase decreases braking forces during stance (Morin et al., 2015).

#### 3.4.3 Practical Implications

From the results of Theme 1 (Phase analysis), two potential practical implications were identified. Firstly, the breakpoints identified using segment angles (i.e. shank and trunk angles) as suggested in British Athletics coaching literature (Crick, 2013a) provided similar ranges of steps (T<sub>start</sub>: 4 - 6; MV<sub>start</sub>: 15 - 17) when compared to using CM-h (T<sub>start</sub>: 4 - 6; MV<sub>start</sub>: 14 - 17) to identify breakpoints. On the other hand, the within-trial comparison showed step differences up to 2.3 steps between using either segment angles or CM-h to identify the breakpoint steps. These opposing results may have resulted from bilateral asymmetries, which influenced the identification of breakpoint steps from shank and trunk angles compared to the holistic centre of mass measure. The similar ranges identified from the different measures suggests that using step-to-step changes in shank and trunk orientations may be appropriate to provide simple feedback about the start and end of the transition phase in applied settings. Sprinting is a complex task where performances are influenced by multiple variables (e.g. step length and step frequency). By subdividing the sprint events into smaller sections, coaches and athletes can focus on more manageable sections of the race before re-constructing the skill as a whole (Seagrave, 1996). The findings of this chapter support the use of changes in touchdown shank and trunk angles to further sub-divide the acceleration and define the steps within the initial acceleration and transition phases, provided that a sufficient number of trials (at least three) are available for analysis. Overall, the results from Theme 1 showed that the first 4 to 9 m of a sprint were part of the initial acceleration phase, while the transition phases ended between 21 to 31 m. In practical situations, it is suggested that coaches use maximal acceleration of either 5 or 10 m to focus on the initial acceleration phase while acceleration distances of 20 to 35 m should be used to develop the transition phase in combination with the initial acceleration phase.

Secondly, the results showed that while the whole acceleration phase could be characterised by changes in different variables throughout, individual phases within sprint acceleration showed their own unique pattern of step-to-step changes in the different variables. These included relatively larger between-step changes in touchdown kinematic variables (especially shank angles and touchdown distances) during the initial acceleration phase compared to the transition phase, while trunk angles increased consistently throughout the initial acceleration and transition phases and before plateauing during the maximal velocity phase. Furthermore, the results showed that while trunk angles (both touchdown and toe-off) and touchdown shank angles showed relatively large between-step changes across the whole sprint, thigh angles (at touchdown and toe-off) and shank angles at toe-off changed relatively little across the whole sprint. Knowledge of these step-to-step changes in variables, which are easily accessible in applied settings contributed to the conceptual understanding of the acceleration and maximal velocity phases. This can ultimately facilitate technical analysis across multiple steps from different phases as a sprint progresses.

From the results of Theme 1 combined with the previous research (e.g. Janshen & Kugler, 2010; Nagahara, Naito, Morin & Zushi, 2014) it could be inferred that during the initial acceleration phase, sprinters should attempt to maximise contact times while still increasing step frequency (i.e. by minimising flight times). This would ensure contact distances are maximised, which were found to be the largest component of step length during the initial acceleration phase (Figure 3.9c). During the transition phase, continued increases in step length are important (Nagahara, Naito, Morin & Zushi, 2014) via increases in flight distances (Figure 3.9d). While running velocities are an important determinant of flight distances (Hunter et al., 2004a), increasing flight distances could be supported by continuing to increase flight times via increases in vertical force production.

#### 3.5 Conclusions

Through a phase analysis (Theme 1), the aim was to investigate differences in stepto-step changes in step characteristics and kinematic variables between initial acceleration, transition and maximal velocity phases. The first research question posed in the introduction of this chapter asked how comparable the breakpoint steps ( $T_{start}$ ) which link the initial acceleration to the transition phase and the breakpoint step ( $MV_{start}$ ) which links the transition to the maximal velocity phase are when identified using different measures. These measures include either CM-h, shank angles or CT≤FT, which were used to identify T<sub>start</sub>, and CM-h or trunk angles, which were used to identify MV<sub>start</sub>. The analysis revealed that the smallest T<sub>start</sub> RMSD (≥ 2.1 steps) was identified between the steps which were detected using CM-h or shank angles. The MV<sub>start</sub> RMSD between steps identified using CM-h and trunk angles was ≥ 2.3 steps. While segment angles only account for changes at individual segments, they may also be more disposed to between-step asymmetries (especially shank angles) which could have affected the within step RMSDs. It was therefore concluded that CM-h provides a more robust and holistic measure that is more representative of the overall changes in posture.

The second research question posed in the introduction asked step-to-step changes of step characteristics and kinematics differ between the initial acceleration phase, transition phase and maximal velocity phase. Using only the best day one and two trials from each participant, steps 1 - 3 were always identified as being in the initial acceleration phase, steps 6 - 13 were identified as the transition phase and steps 17 onwards were identified as the maximal velocity phase. Overall, during the initial acceleration phase, step characteristics, spatial-temporal variables and segment orientations at touchdown showed the largest step-to-step changes while toe-off distances and toe-off thigh and shank orientations remained relatively consistent. This meant that contact distances increased over the first three steps although contact times decreased rapidly. The transition phase was characterised by a reduction in the magnitude of step-to-step changes of the variables investigated. Specifically, step-to-step changes in contact distances started to plateau as step-to-step increases, which were smaller than during the initial acceleration phase, were approximately matched by the step-to-step decreases in toe-off distances. Furthermore, step-to-step increases in step lengths continued due to increases in flight distance. From step 17 onwards, changes in postural variables plateaued and the participants started the maximal velocity phase. This phase is characterised by a plateauing of the kinematic variables and small increases in step velocity, step length and flight distance.

#### **3.6 Chapter summary**

This chapter aimed to investigate differences in step-to-step changes in step characteristics and kinematic variables between the initial acceleration, transition and maximal velocity phases. The purpose was to increase knowledge of the initial acceleration, transition and maximal velocity phases and assist with the development of technical models for different phases of sprinting. A novel finding from the current chapter was the consistency of the T<sub>start</sub> and MV<sub>start</sub> step ranges identified between two days. This further verifies the location of these breakpoint steps and reinforces the idea proposed previously to sub-divide the acceleration phase in sprinting. If at least three trials were available for analysis, it was concluded that although segment angles may be appropriate measure to identify phases in sprint acceleration in more applied settings, CM-h represents a more holistic measure to quantify total body changes. CM-h was therefore adopted for the current chapter to sub-divide the acceleration phase in sprinting.

Using CM-h as the discriminating measure to sub-divide the acceleration phase, steps 1-3 were identified as being in the initial acceleration phase, steps 6 – 13 were identified as being in the transition phase and steps 17 onwards were identified as being in the maximal velocity phase. The initial acceleration phase in characterised by large changes in CM-h and touchdown distances. These are likely influenced by changes in shank and trunk angles. During the transition phase, further increases in CM-h were likely due to further increases in trunk angles while shank angles started to plateau. These changes in touchdown distances were likely linked to increasing demands placed on vertical force production as contact times decreased. Toe-off distances on the other hand showed little change with increases in this variable possibly due to changes in trunk angle which limited the clockwise rotation of the thigh (i.e. thigh became more vertical at toe-off). This slowed increase in toe-off distances may be important to allow sufficient propulsive force application during the latter half of ground contact.

Theme 1 (Phase analysis) aimed to increase understanding of how the acceleration phase in sprinting is structured. Specifically, how step-to-step changes in the variables more accessible to coaches and sport scientists are associated with the initial acceleration, transition and maximal velocity phases in sprinting. While the results in this chapter revealed some novel insight into step-to-step changes in kinematics, the changing musculoskeletal demands between these phases and their implications on performance are still not well understood. A joint kinetic analysis of steps within the initial acceleration, transition and maximal velocity phases will provide a better understanding of the technique used during these phases of sprinting.

# **Chapter 4 -** Technique analysis: Changes in joint kinematics and kinetics between different phases of a sprint

# 4.1 Introduction

In Chapter 3 the steps occurring in the initial acceleration, transition and maximal velocity phases were identified. The results in Chapter 3 also revealed that there are some considerable changes in step characteristics and kinematic variables between the initial acceleration, transition and maximal velocity phases. As sprinters accelerate from lower to higher velocities, performance is influenced by the sprinters' ability to continue to produce a net horizontal propulsive force (Rabita et al., 2015) while producing sufficiently large vertical forces to provide an appropriate flight time to allow the sprinter to prepare for the next stance phase (Hunter et al., 2005). Against the backdrop of decreasing ground contact times, there is an increasing demand to generate the larger vertical GRF as velocities increase (Weyand et al., 2000).

Joint kinetics have previously been reported in sprinting, however the majority of the data has focused on individual steps from the initial acceleration (Jacobs & van Ingen Schenau, 1992; Charalambous et al., 2012; Debaere, Delecluse et al., 2013; Bezodis et al., 2014), transition (Johnson & Buckley, 2001; Hunter et al., 2004) and maximal velocity phases (Mann and Sprague, 1980; Mann, 1981; Bezodis et al., 2008). While these studies provided important insights into joint function in sprinting at specific steps, it is difficult to assess how musculoskeletal characteristics change between the different phases during maximal sprinting. The few studies that have reported joint kinetics data across multiple steps indicated some important changes in the energy absorption and generation strategies (Ito et al., 1992; Braunstein et al., 2013) and joint moments (Yu et al., 2016) at the ankle and knee. However, these multi-step studies have either only reported general trends in abstract form (e.g. Ito et al., 1992; Braunstein et al., 2013) or only focused on joint moments (Yu et al., 2016). Since the kinematic changes identified in Chapter 3 are likely driven by the work done at the joints, a complete analysis of the changing joint kinetics between initial acceleration, transition and maximal velocity phases will add valuable information to the understanding of changes in technical and physical demands between phases of maximal sprinting.

The aim of this study was to investigate the changes in joint kinetics between the initial acceleration, transition and maximal velocity phases. This investigation will be based on comparing a step from each of the initial acceleration, transition and maximal velocity phases as identified as part of Theme 1 (Figure 4.1). Based on these data, step three (black arrow) was identified to represent the initial acceleration phase, step nine (blue arrow) was selected to represent the transition phase and step 19 (red arrow) to represent the maximal velocity phase.



**Figure 4.1.** Similar to figure 3.6 shows the steps that occurred in the initial acceleration, transition and maximal velocity phases (shaded areas) as identified in Chapter 3. The coloured arrows identify the steps investigated in the current Chapter.

Using an inverse dynamics analysis, research question iii – '*How do the joint kinematics and kinetics change between the initial acceleration, transition and maximal velocity phases?*' will be addressed. With reference to the main research question, this will address changes in joint kinematics, joint moments, joint power and joint work between steps three, nine and 19. The purpose of Theme 2 (Technique analysis) was to provide a new understanding of the changes in musculoskeletal characteristics as a sprint progresses, which will add valuable novel information to the body of knowledge of maximal sprinting.

## 4.2 Methods

#### 4.2.1 Participants

Thirteen experienced sprinters (Table 4.1) gave written informed consent to participate in the study after ethical approval was obtained from the university. The participants were injury free throughout the testing.

ID	Gender	Body Mass [kg]	Height [m]	60 m/100 m PB [s]*
P02	Male	73.0	1.79	6.70 / 10.35
P03	Male	74.1	1.78	6.73 / 10.54
P04	Female	69.3	1.76	7.60 / 11.69
P06	Male	76.3	1.83	6.93 / 10.68
P07	Male	74.2	1.73	6.99 / 10.95
P08	Male	70.6	1.82	7.09 / 11.18
P09	Male	77.7	1.88	7.00 / 10.88
P10	Male	82.6	1.78	6.88 / 10.86
P11	Male	74.0	1.70	6.87 / 10.89
P12	Male	71.6	1.73	7.01 / 10.79
P13	Male	75.8	1.79	7.01 / 11.40
P14	Female	63.3	1.67	7.61 / 11.99
P15	Female	70.3	1.82	7.91 / 12.68

Table 4.1. Participant Characteristics.

P02, P03 and P04 are the same as in Chapter 3; \* PBs before testing commenced

#### 4.2.2 Protocol

Prior to the data collection, the participants' height, body mass and shoe mass were taken. The participants were instructed to complete their normal sprint specific warm-ups. The required data from steps three, nine and 19 were collected over various testing sessions during the 2015/2016 season. During the testing sessions, each participant performed a total of three to six maximal effort sprints over distances up to 40 m during which the starting blocks were placed in a specific location for each participant to ensure that the required step made contact with the force plates without any need for targeting. For step three, the distance between the force plates and the starting line ranged between 2.90 - 3.10 m while for steps 9 and 19 the distances ranged between 12.50 - 13.50 m and 30.00 - 36.00 m, respectively. Between each trial participants had a minimum of 5 minutes rest to ensure full recovery.

#### 4.2.3 Data Collection

Testing was conducted at the National Indoor Athletics Centre in Cardiff. Sagittal plane kinematic data were collected using one DV digital camera (Sony Z5, Sony Corporation, Tokyo, Japan) with a 5.5 m horizontal field of view, which was placed a minimum of 15.0 m from the running lane (Figure 4.2) with the centre of the image perpendicular to the centre of the force plates. The camera recorded in HD (1440 × 1080) at 200 Hz. The iris was fully open and the shutter speed was 1/600 s. Two Kistler force plates (type 9287BA and 9287CA, Kistler Instruments Corporation, Winterthur, Switzerland) sampling at a 1000 Hz were situated on the inside track of

the running straight and covered with the same Mondo surface as the surrounding track. The GRF data was collected using CODAmotion analysis (version 6.68/MPx30, Charnwood Dynamics Ltd, Leicester, UK). GRF and kinematic data were synchronised to within 0.001 s using a series of illuminating LEDs light (Wee Beastie, UK).



Figure 4.2. Set-up.

To obtain the data required for camera calibration, a pole with six markers was moved sequentially through five locations in the camera view. This allowed a  $4.000 \text{ m} \times 1.900 \text{ m}$  plane to be calibrated. As with Chapter 3, a pole with six points of known locations was then placed at various known locations within the calibrated plane. This would later be used to estimate the accuracy of coordinate reconstruction.

# 4.2.4 Data Processing

The videos were extracted from the tapes using Dartfish Team Pro 6.0 (Dartfish) and then converted to .avi format and de-interlaced in VLC 2.1.3 (VideoLan, France). The videos were then digitised in Matlab (The MathWorks Inc., USA, version R2014a) using an open source digitising package (Hedrick, 2008) at full resolution and 2 × zoom. Digitising commenced at toe-off of the stance phase preceding the stance phase being investigated and ended ten frames after the touchdown of the contact after the one being investigated. Eighteen points on the human body (Vertex, C7, hip, shoulder, elbow, wrist, knee, ankle, MTP joint centres and distal end of the halluces) were digitised. A further point was used as a timing mark to identify the touchdown (first frame of visible ground contact) and toe-off (first

frame after the foot left the ground) events of the contact of interest and the contact after. The digitised trials were then reconstructed in Matlab using an open source 8 parameter 2D DLT camera calibration and point reconstruct function (Woltring and Huiskes, 1985; Meershoek, 1997; http://isbweb.org/software/) which was edited to include a ninth parameter 2D DLT which accounted for lens distortion (Walton, 1981). Digitising reliability was assessed by re-digitised one trial twice (see appendix A4).

The reconstructed kinematic data were then imported into a custom written Matlab script and synchronised to the force plate data using the information from the synch lights. Following that the kinematic data was filtered. In order to ensure the joint moment data were free of artefacts caused when kinematic and kinetic data are filtered with mismatched cut-off frequencies (Bezodis et al., 2013), it was decided to filter both the kinematic and kinetic data with the same cut-off frequency. Since stance leg joint moments will be calculated later in this chapter, it was decided that the selected cut-off frequency should be chosen to minimise the signal-to-noise ratio within the landmarks on the stance leg and trunk. The optimal cut-off frequency was determined based on the autocorrelation method (Challis, 1999). To ensure that differences between the steps were not due to differences in filtering, a mean cut-off frequency was calculated from all individual cut-offs. This mean cut-off (26 Hz) was therefore applied to filter all the kinematic and kinetic time-history data from all steps using a fourth-order Butterworth digital filter (Winter, 2009).

Data from de Leva (1996) was used to calculate the inertia data for all the segments except the foot. For the foot segments, each participants shoe mass was added to the mass of the foot segments. Data identifying the centre of mass location and mass distribution of the fore and rear foot segment from Bezodis et al. (2014) was used define the inertial properties of the fore and rear foot. The mass of the sprint shoe was also split into a fore and rear foot segment according to the mass ratio data from Bezodis et al. (2014). Whole-body CM was subsequently calculated using the summation of segmental moments approach (Winter, 2009). Segment orientations were calculated with 0° representing a horizontal orientation and a positive increase an anti-clockwise rotation. In addition, descriptions of segment rotations as clockwise or anti-clockwise are always relative to the direction of motion

being left to right. Joint angles were calculated as the 2D angle between two vectors with extension of the hip, knee, ankle and MTP joints defined as positive (Figure 4.3). All linear and angular time-displacement histories were differentiated using a three-point central difference method (Miller & Nelson, 1976) via the gradient function in Matlab. Angular and linear velocity data were differentiated again to yield linear and angular acceleration data. Step velocity, step length and step frequency were calculated according to the methods outlined in Chapter 3 (section 3.2.7).



Figure 4.3. Convention used to describe positive changes (extension) in joint kinematic and kinetics.

Since the touchdown and toe-off events for each step were defined using the 1000 Hz force data, the kinematic data was resampled at 1000 Hz using an interpolating cubic spline. This would allow a more precise determination of touchdown and toe-off joint kinematic variables, as the first 200 Hz video frames could occur 0.004 s after touchdown or toe-off. Horizontal external power was selected as a performance measure for steps three and nine. The incoming CM velocity was calculated using CM displacement data as outlined in Bezodis et al. (2010). The first derivative of a first order polynomial fitted through 10 frames prior to touchdown was used to calculate the incoming CM velocity. This CM velocity together with the measured GRF data was used to calculate the average external power will be described in more detail below. Step velocity was used as the performance measure for step 19. The step characteristics were calculated according to the methods outlined in Theme 1 (Chapter 3: section 3.2.7).

Before filtering the GRF data, data from the individual force channels were exported using the CODAmotion software. Initially the appropriate force channels were summed to calculate the vertical, anterior-posterior and medio-lateral forces. The vertical forces were used to identify the touchdown and toe-off events. Touchdown was defined as the first frame when the vertical ground reaction force rose above 10 N. Toe-off was defined as the first frame after vertical ground reaction force fell below 10 N. For all the variables reported directly from the GRF data, the raw forces were filtered with a higher cut-off frequency (~170 Hz) which was determined for each force trace using the autocorrelation function described above.

Resultant forces were calculated from the vertical and anterior-posterior GRF. Peak resultant, vertical and anterior-posterior (braking and propulsive) forces were identified from the filtered forced data. Braking, propulsive, net anterior-posterior and vertical (body weight removed) impulses were calculated via numerical integration (trapezium rule) and expressed relative to the participant's body mass to reflect the change in velocity of the centre of mass. Using the relative anterior-posterior impulse, the change in velocity across each frame of ground contact was calculated and combined with the incoming CM velocity in order to obtain the absolute instantaneous velocity throughout stance. External power was then determined as the product of the instantaneous horizontal velocity and horizontal force. Horizontal external power across the entire stance phase was subsequently averaged and normalised for use as a measure of performance (Bezodis et al., 2010).

The centre of pressure (COP) was calculated from the individual force channels using the equations provided by the manufacturer of the force plates (Kistler Instruments Corporation, Winterthur, Switzerland) and accounting for the thickness of the track surface. When the ground contact occurred across both plates, the global COP was calculated as the sum of the products between each plate's COP and a weighting factor (Exell et al., 2012). The centre of plate two (Figure 4.2) was set as the origin of the two force plates. This coincided with the origin of the global coordinate system. The centre of pressure coordinates from force plate 1 were therefore offset by 0.906 m in the y direction. Finally, to match the GRF and centre of pressure data with kinematic data for joint kinetics calculations these data were

down sampled to 200 Hz and filtered using a bi-directional Butterworth filter with the previously determined cut-off frequency of 26 Hz.

## 4.2.4.1 Inverse dynamics analysis

The synchronised kinematic data and force data (both sampled at 200 Hz and filtered at 26 Hz) were used to calculate the internal joint forces and moments. This was done using a 2D inverse dynamics analysis according to Winter (2009) starting with the measured external GRF and moving up the body to calculate the joint kinetics at the MTP, ankle, knee and hip. Since the MTP has previously been shown to play an important role in sprinting (Stefanyshyn & Nigg, 1997; Bezodis et al., 2012) it was decided to include this joint in the analysis. The fore foot segment and MTP joint were only included in the calculation when the COP acted in front of the MTP joint (Stefanyshyn & Nigg, 1997). Furthermore, the inertial properties of the fore foot were assumed to be negligible and therefore the MTP joint (Stefanyshyn & Nigg, 1997). Suith et al., 2014).

#### Nomenclature for the inverse dynamics analysis

F	Force
а	Acceleration
g	Gravity
m	Mass
i	Segment
СМ	Centre of mass
$Fy_i$	Horizontal joint reaction force at proximal endpoint of the ith segment
Fz <sub>i</sub>	Vertical joint reaction force at the proximal endpoint of the $i^{\mbox{th}}$ segment
ay <sub>i</sub>	Horizontal acceleration of the ith segment
az <sub>i</sub>	Vertical acceleration of the ith segment
$Fy_{i-1}$	Horizontal joint reaction force at the distal endpoint of the ith segment
$Fz_{i-1}$	Vertical joint reaction force at distal endpoint of the ith segment
М	Moment
I <sub>i</sub> .	Moment of inertia of the i <sup>th</sup> segment
$lpha_i$	Angular acceleration of the ith segment
$M_{pi}$	Moment acting on the proximal endpoint of the ith segment
M <sub>di</sub>	Moment acting on the distal endpoint of the ith segment
$r_i p$	Moment arm between the proximal end of the segment and the CM
$r_i d$	Moment arm between the distal end of the segment and the CM
1100	memori and betheen the distal end of the beginning and the em

j	Joint
JP <sub>j</sub>	Joint power of the j <sup>th</sup> joint
$\omega_j$	Angular velocity of the j <sup>th</sup> joint
$W_{nj}$	Joint work of the n <sup>th</sup> power phase of joint j
JP <sub>j</sub>	Joint power of the ith joint
Σ	Sum of

Net joint forces were calculated according to Newton's 2<sup>nd</sup> law of linear motion (Equation 4.1).

$$\sum F_i = m_i \times a_i$$
 [Equation 4.1]

The free body diagram (Figure 4.4) below shows the forces acting on the i<sup>th</sup> segment in both the vertical (z) and anterior-posterior direction (y). Using the known linear acceleration and forces acting on the distal end of the segment, the unknown forces acting on the proximal end of the segment could thus be calculated.



Figure 4.4. Free body diagram illustrating the forces acting on the i<sup>th</sup> segment.

The vertical and anterior-posterior internal joint forces were thus calculated using the following equations:

$$Fy_i = m_i \times ay_i - Fy_{i-1}$$

$$Fz_i = m_i \times az_i - m_i \times g - Fz_{i-1}$$
[Equation 4.2]  
[Equation 4.3]

The resultant joint moments were calculated using Newton-Euler equation (Equation 4.4) which describes the combined translational and rotational dynamics

of a rigid segment. Here, the sum of the moments acting on a segment is equal to the segment's rate of change in angular momentum.

$$\sum M_i = I_i \times \alpha_i$$
 [Equation 4.4]



Figure 4.5. Free body diagram illustrating the forces and moments acting on the ith segment.

The free body diagram depicted in figure 4.5 above shows all the moments acting on a segment. Starting from the distal end of the fore foot segment where the moment is known, the moment at the proximal end of the segment was calculated using the following equation.

$$M_{pi} = (Fz_i \times r_i py) + (Fy_i \times r_i pz) + (Fz_{i-1} \times r_i dy) + (Fy_{i-1} \times r_i dz) + (I_i \times \alpha_i) - M_{di}$$
 [Equation 4.5]

The joint moments were reported using the same convention as the angular data (Figure 4.3) with extension and plantar flexion defined as positive. MTP, ankle, knee and hip joint powers were calculated as the product of the joint moment and joint angular velocity (rad·s<sup>-1</sup>) (Equation 4.6).

$$JP_i = M_{pi} \cdot \omega_i$$
 [Equation 4.6]

Based on the definition of Winter (2009), joint power phases were identified as periods of positive or negative power. The work during each power phase was calculated via numerical integration (trapezium rule).

$$W_{nj} = \int_{t_2}^{t_1} J P_i dt \qquad [Equation 4.7]$$

Joint moments and joint angular velocity values were used to determine whether joint power was positive or negative throughout the stance phases of steps three, nine and 19. For example, when both the net joint moment was extensor dominant and the joint angular velocity was positive (joint extending), the resulting positive power phase was described as a positive extensor power phase and positive extensor work.

At the MTP, ankle and hip joints two main power phases were identified (Figure 4.6). At the MTP and ankle joints a plantar flexor moment power abortion phase (MTP-; A-) was followed by a plantar flexor power generation phase (MTP+; A+). At the hip joint a hip extensor moment power generation phase (H+) was followed by a hip flexor power absorption phase (H-).



Figure 4.6. Definition of the power phases for the MTP, ankle and hip joints.

Up to four power phases were identified at the knee joint (Figure 4.7). The knee flexors generated energy (Kf+) while a knee flexor moment and a knee flexor angular velocity were present. The knee extensors absorbed energy (Ke-) when a knee flexor angular velocity and a knee extensor moment were present. The knee extensors generated energy (Ke+) when a knee extensor moment and knee extensor angular velocity were present and the knee flexor absorbed energy (Kf-) when a knee flexor moment and knee extensor angular velocity were present.



Figure 4.7. Definition of the power phases for the knee during steps three, nine and 19.

#### 4.2.5 Data normalisation

The calculated joint angular velocities (deg·s<sup>-1</sup>), moments (Nm), powers (W) and work (J) for each participant were normalised according to the recommendations of Hof (1996) with height used for linear scaling. Angular velocities were normalised using gravity (g; 9.81 m·s<sup>-2</sup>) and height ( $\sqrt{\frac{g}{Height}}$ ), joint moments and work were normalised using body weight and height (BW \* Height). Joint powers were normalised to body mass (BM), gravity and height ( $BM * g^{\frac{3}{2}} * Height^{\frac{1}{2}}$ ) according to Bezodis et al. (2010).

#### 4.2.6 Data presentation

The best step three, nine and 19 trials from each participant was selected for further analysis. The best step three and nine trial was based on identifying the trial during which the participant produced the largest normalised average external horizontal power. This was based on the fact that power production is of critical importance during sprint acceleration and ultimately determines acceleration of the participants (Bezodis, et al., 2010). The best step 19 trial was selected based on identifying the trial where the participants achieved the largest maximal step velocity as this reflect a higher level of performance during the maximal velocity phase. Minimum and maximal joint kinematic and kinetic values and associated timings (absolute (s) and percentages of stance (%)) were extracted from the time-histories. The time-histories for each ground contact were then time-normalised to 101 data points using a cubic spline. The time-normalised GRF, joint kinematics, joint kinetic data as well as the segment angles and angular velocities were averaged across participants to create an ensemble average for each step. The mean time-normalised data for each step was presented relative to the mean contact time for the relevant step.

# 4.2.7 Data analysis

Descriptive statistics (mean  $\pm$  SD) were calculated for all the discrete variables. In order to clarify the meaningfulness of the differences, magnitude-based inferences were computed (Batterham & Hopkins, 2006). The mechanistic inference was used to quantify the difference being either positive, trivial or negative. The differences between means (step: 9-3; 19-3; 19-9) were calculated using post-only crossover

analysis (Hopkins, 2006). The confidence interval with which the inferences were made (after adjusting for the number of comparisons, three) was 97%. To evaluate the meaningfulness of the difference, a Cohen's effect size of 0.2 was used as the threshold for the smallest worthwhile change (Winter et al., 2014). The probability (percentage and qualitative description) that the true effect size was bigger than 0.2 was defined as: very unlikely: <5%; unlikely: 5% - 24.9%; possibly 25 - 74.9%; likely: 75% - 94.9%; very likely: 95% - 99.4% and most likely >99.5% (Hopkins, Marshall, Batterham & Hanin, 2009). When the outcome of the effect had a >5% chance of being both positive and negative, the mechanistic outcome was described as unclear. Otherwise, the mechanistic outcome was clear with differences being either positive or negative. To evaluate the magnitude of the observed differences between the steps, the scale based on Hopkins et al. (2009) was used to quantify the effect sizes: 0.0 (trivial), 0.2 - 0.59 (small), 0.6 - 1.19 (moderate), 1.2 - 1.99 (large), 2.0 - 3.99 (very large) and >4.0 (extremely large).

# 4.3 Results

#### 4.3.1 Kinematic variables

Starting with the step characteristics, the increases in step velocity (Table 4.2) from step three to step nine were most likely extremely large and between steps nine and 19 were most likely very large. Increases in vertical CM velocity prior to touchdown were most likely large between step three and nine and most likely moderate between steps nine and 19. Step length increases were most likely very large between steps three and nine and most likely very large between steps nine and 19.

		Ste	ep 3	Ste	ep 9	Step	o 19				
		Mean	SD	Mean	SD	Mean	SD				
Step velocity	[m⋅s⁻¹]	5.81	0.24	8.36	0.46	9.67	0.58				
Vertical CM velocity	[m⋅s⁻¹]	-0.24	0.13	-0.52	0.17	-0.69	0.11				
Step length	[m]	1.37	0.09	1.92	0.19	2.25	0.21				
Step frequency	[Hz]	4.27	0.34	4.39	0.45	4.33	0.43				
NAHP		0.69	0.12	0.49	0.16	0.20	0.11				
Contact time	[s]	0.155	0.014	0.123	0.013	0.105	0.010				
Flight time	[s]	0.080	0.015	0.107	0.020	0.128	0.022				
Step time	[s]	0.236	0.019	0.230	0.028	0.233	0.026				

 Table 4.2. Mean ± SD values for selected step characteristics, performance and temporal variables for steps three, nine and 19 across all participants.

- NAHP: normalised average horizontal power

Differences in step frequency were unclear between steps three and nine and between steps three and 19 and possibly trivial between steps nine and 19.

Decreases in contact times were most likely very large from steps three to nine to 19. Flight time increases were most likely large between steps three and nine and most likely moderate between steps nine and 19.

The differences in CM-h, trunk and shank angles at touchdown (Table 4.3) were most likely large to extremely large in all three comparisons.

Table 4.3.         Mean ± SD of touchdown CM-h, trunk and shank angles for steps three, nine and 19										
		Step 3	•	Step	9	Step 19				
		Mean	SD	Mean	SD	Mean SD				
CM-h	[%]	51	2	54	1	57 1				
θtrunk	[°]	46	9	64	7	81 3				
$\theta_{shank}$	[°]	63	5	87	4	97 3				

The increases in horizontal foot velocities at touchdown (Table 4.4) between steps three and nine were most likely large and very likely moderate between steps nine and 19. Increases in downward foot velocities were most likely large between steps three and nine and very likely moderate between steps nine and 19. The differences in touchdown and toe-off distances between steps three, nine and 19 were most likely large to extremely large.

 Table 4.4. Mean ± SD horizontal and vertical foot velocity and touchdown and toe-off distances during steps three, nine and 19.

Measure		Step 3		Ste	p 9	Step 19		
	Unit	Mean	SD	Mean	SD	Mean	SD	
Horizontal foot velocity	[m⋅s <sup>-1</sup> ]	0.45	0.86	1.96	0.90	2.53	0.65	
Horizontal foot velocity relative to step velocity	[m⋅s⁻¹]	-5.36	0.80	-6.41	1.00	-7.14	1.00	
Vertical foot velocity	[m⋅s <sup>-1</sup> ]	-1.75	0.45	-2.44	0.43	-2.96	0.37	
Vertical foot velocity relative to vertical CM velocity prior to TD	[m⋅s⁻¹]	-1.51	0.39	-1.93	0.43	-2.27	0.38	
Touchdown distance	[m]	0.055	0.057	0.275	0.060	0.359	0.046	
Toe-off distance	[m]	-0.731	0.037	-0.641	0.041	-0.546	0.028	

# 4.3.2 GRF variables

Mean and peak vertical GRF (Table 4.5) increased from steps three to nine to 19. These differences in were most likely very to extremely large. The absolute (and relative) timings of the peak vertical forces occurred at  $0.073 \pm 0.017$  s ( $47 \pm 9\%$ ) during step three,  $0.039 \pm 0.014$  s ( $32 \pm 12\%$ ) during step nine and  $0.030 \pm 0.008$  s ( $29 \pm 8\%$ ) during step 19. Differences between in the absolute time at which peak

vertical forces occurred were most likely large between steps three and nine and between steps three and 19.

Table 4.5. Mean ± SD	of stance mean and	maximum	resultant GRF	from step	os three,	nine and	19.

		Step	3	Step 9		Step	19
		Mean	SD	Mean S	SD	Mean	SD
Mean resultant force	[BW]	1.6	0.2	1.9 (	).2	2.2	0.2
Maximum resultant force	[BW]	2.3	0.2	3.0 (	).4	3.8	0.3
RF	%	31	3	12 3	3	4	2

Decrease in mean horizontal forces between step three, nine and 19 (Figure 4.8a) were most likely very large to extremely large. Differences in peak horizontal braking forces were most likely large to very large between steps three to nine to 19 (Figure 4.8a). Differences in the durations of the braking phase were most likely very large between steps three ( $0.012 \pm 0.005$  s;  $8 \pm 3\%$  of stance) and nine ( $0.034 \pm 0.011$  s;  $27 \pm 6\%$  of stance) and most likely moderate between steps nine and 19 ( $0.043 \pm 0.008$  s;  $41 \pm 5\%$  of stance). Decreases in peak propulsive forces were most likely moderate between steps three and 19 (Figure 4.8a).



**Figure 4.8.** Mean  $\pm$  SD time-histories of horizontal (a) and vertical (b) ground reaction force data for step three (black), step nine (blue) and step 19 (red). The tables below the respective figures show the descriptive results of the MBI analysis of the differences between the three steps. For each comparison, there is a qualitative description of the probability of the standardised differences being larger than 0.02, followed by the size (standardised effect) and direction of the differences.

The absolute (% of stance) occurrence for the peak propulsive forces for steps three, nine and 19 were  $0.109 \pm 0.012$  s (70 ± 2%),  $0.088 \pm 0.010$  s (71 ± 2%) and  $0.075 \pm 0.008$  s (72 ± 2%) respectively. Durations of the propulsive phase showed most likely extremely large decreases from step three ( $0.143 \pm 0.015$  s; 92 ± 3% of stance) to step nine ( $0.089 \pm 0.004$  s; 73 ± 6% of stance) and most likely very large decreases between steps nine and 19 ( $0.062 \pm 0.004$  s; 59 ± 5% of stance).

Increases in relative vertical impulse (Table 4.6) were most likely very large between steps three and nine and most likely moderate between steps nine and 19. The decrease in relative anterior-posterior impulses between steps three and nine was most likely extremely large and between steps nine and 19 were most likely very large. The increase in relative braking impulse (Table 4.6) was most likely large between steps three and nine and most likely very large between steps nine and 19. The decrease in relative propulsive impulse (Table 4.6) between steps three and nine and most likely very large between steps nine and 19.

nonzontal velocity decrease and increase during steps three, nine and 19 across all participants.											
			Step 3		9	Step	19				
		Mean	SD	Mean	SD	Mean	SD				
Change in vertical velocity	[m⋅s⁻¹]	0.66	0.14	1.00	0.18	1.18	0.15				
Net change in horizontal velocity	[m·s <sup>-1</sup> ]	0.74	0.05	0.28	0.06	0.08	0.04				
Horizontal velocity decrease	[m⋅s⁻¹]	-0.03	0.02	-0.10	0.05	-0.19	0.04				
Horizontal velocity increase	[m·s <sup>-1</sup> ]	0.77	0.04	0.38	0.03	0.27	0.03				

**Table 4.6.** Mean  $\pm$  SD changes in vertical, net horizontal velocity as well as the mean  $\pm$  SD horizontal velocity decrease and increase during steps three, nine and 19 across all participants.

Across participants, there was a trend for the relative braking impulse to increase with increases in the horizontal velocity of the foot immediately prior to touchdown of steps three, nine and 19 as well as touchdown distance during steps nine and 19 (Figure 4.9).



**Figure 4.9.** Scatter-plots and trend lines for steps three (black), nine (blue) and 19 (red) for a) foot touchdown velocity and b) touchdown distance against relative the relative braking impulse.

#### 4.3.3 Joint kinematics and kinetics

#### 4.3.3.1 MTP Joint

At the MTP joint, similar kinematic patterns were visible between steps three, nine and 19. During ground contact, the MTP joint angle initially plantar flexed before dorsiflexing from  $0.027 \pm 0.013$  to  $0.136 \pm 0.014$  s ( $18 \pm 9$  to  $87 \pm 2\%$  of stance), from  $0.029 \pm 0.006$  to  $0.104 \pm 0.012$  s ( $24 \pm 5$  to  $85 \pm 3\%$  of stance) and from  $0.027 \pm 0.004$  to  $0.089 \pm 0.009$  s ( $26 \pm 3$  to  $85 \pm 2\%$  of stance) during steps three, nine and 19 respectively (Figure 4.10a). After the MTP joint reached the minimum dorsiflexion angles, the MTP joint plantar flexed until toe-off. The differences in peak dorsiflexion angular velocity were likely moderate between steps three (- $317 \pm 65$ (dimensionless units)) and nine (- $390 \pm 91$ ) and most likely large between steps nine and 19 (- $507 \pm 81$ ).

The MTP moment (Figure 4.10c) was plantar flexor dominant throughout stance, reaching peaks of  $0.03 \pm 0.01$  (step 3),  $0.03 \pm 0.01$  (step 9) and  $0.04 \pm 0.02$  (step 19). The peak normalised negative power was  $-0.43 \pm 0.13$  (step three),  $-0.66 \pm 0.22$  (step nine) and  $-0.90 \pm 0.44$  (step 19). The increase in peak negative power was very likely moderate between steps three and nine and likely moderate between steps nine and 19. Differences in peak positive power were possibly small between steps three ( $0.28 \pm 0.09$ ) and nine ( $0.32 \pm 0.09$ ), likely moderate between steps nine and 19 ( $0.43 \pm 0.19$ ).



Figure 4.10. Mean ± SD MTP angle (a), normalised MTP angular velocity (b), normalised MTP moment (c) and normalised power between steps three (black), nine (blue) and 19 (red). The tables below the respective figures show the descriptive results of the results of the MBI analysis of the differences between the three steps. For each comparison, there is a qualitative description of the probability of the standardised differences being larger than 0.02, followed by the size (standardised effect) and direction of the differences.

The energy absorbed by the MTP joint increased from steps three (-0.013  $\pm$  0.005), nine (-0.018  $\pm$  0.006) and 19 (-0.018  $\pm$  0.009; Figure 4.11). On each step, the energy generated at the MTP joint (Step three: 0.003  $\pm$  0.001; Step nine: 0.002  $\pm$  0.001; Step 19: 0.003  $\pm$  0.001) was relatively small compared to the energy absorbed on the step.



**Figure 4.11.** Mean  $\pm$  SD normalised negative (MTP-) and positive (MTP+) MTP work for steps three (black), nine (blue) and 19 (red). The table shows the results of the MBI analysis of the differences between the three steps. For each comparison, there is a qualitative description of the probability of the standardised differences being larger than 0.02, followed by the size (standardised effect) and direction of the differences.

# 4.3.3.2 Ankle Joint

Similar angular kinematic and kinetic patterns at the ankle were exhibited during steps three, nine and 19 (Figure 4.12a). Increases in touchdown ankle angles were most likely moderate between steps three  $(111 \pm 8^{\circ})$  and nine  $(120 \pm 6^{\circ})$  and most likely large between steps nine and 19  $(130 \pm 7^{\circ})$ . The differences in dorsiflexion ROM were most likely moderate (Figure 4.12a) between steps three  $(18 \pm 4^{\circ})$  and nine  $(24 \pm 4^{\circ})$  and most likely large between steps nine and 19  $(32 \pm 7^{\circ})$ . The resulting dorsiflexion angular velocity peaked at  $0.016 \pm 0.003$  s (step 3),  $0.016 \pm 0.004$  s (step 9) and  $0.015 \pm 0.003$  s (step 19). Differences in peak dorsiflexion angular velocity (Figure 4.12b) between steps three (-261 ± 62) and step nine (-337 ± 48) were very likely moderate to large. The differences in peak dorsiflexion angular velocity were most likely large between steps nine and 19 (-448 ± 86).



Figure 4.12. Mean ± SD ankle angle (a), normalised ankle angular velocity (b), normalised ankle moment (c) and normalised ankle power between steps three (black), nine (blue) and 19 (red). The tables below the respective figures show the descriptive results of the results of the MBI analysis of the differences between the three steps. For each comparison, there is a qualitative description of the probability of the standardised differences being larger than 0.02, followed by the size (standardised effect) and direction of the differences.

During the second half of stance, no clear differences in plantar flexion ROM (Figure 4.12a) were observed between steps three  $(48 \pm 5^{\circ})$ , nine  $(47 \pm 5^{\circ})$  and 19  $(44 \pm 5^{\circ})$ . The ankle plantar flexion angular velocities (step 3: 482 ± 62; step 9: 510 ± 66; step 19: 543 ± 86) peaked 0.140 ± 0.015 s (step 3), 0.110 ± 0.015 s (step 9) and 0.089 ± 0.012 s (step 19) after touchdown.

Differences in peak ankle moments (Figure 4.12c) were most likely moderate between steps three (0.18  $\pm$  0.02) and nine (0.21  $\pm$  0.03) and most likely moderate between steps nine and 19 (0.24  $\pm$  0.04). The peaks occurred at 0.087  $\pm$  0.017 s  $(56 \pm 8\% \text{ of stance}), 0.060 \pm 0.009 \text{ s} (49 \pm 5\% \text{ of stance}) \text{ and } 0.048 \pm 0.008 \text{ s} (46 \pm 1.0000 \text{ s})$ 6% of stance) during step three, nine and 19, respectively. The differences in the absolute timings of the peaks of the plantar flexor ankle moment were most likely very large between steps three and nine most likely moderate between steps nine and 19. The peak negative ankle joint power (step 3: -1.18 ± 0.42; step 9: -2.20 ± 0.61; step 19:  $-3.66 \pm 1.02$ ) occurred at 0.023  $\pm 0.003$  s (15  $\pm 3\%$  of stance), 0.024  $\pm$  0.006 s (20  $\pm$  5% of stance) and 0.023  $\pm$  0.003 s (22  $\pm$  3% of stance) after touchdown of steps three, nine and 19 respectively. Peak joint power generation (step 3: 2.32 ± 0.48; step 9: 2.73 ± 0.90; step 19: 3.61 ± 1.06) occurred at 0.122 ± 0.013 s (79 ± 2% of stance), 0.091 ± 0.011 s (74 ± 4% of stance) and 0.076 ± 0.008 s  $(73 \pm 2\%)$  of stance) respectively. The differences in peak power generation were likely small between steps three and nine and very likely moderate between steps nine and 19.



**Figure 4.13.** Mean  $\pm$  SD normalised negative (A-) and positive (A+) ankle work for steps three (black), nine (blue) and 19 (red). The table shows the results of the MBI analysis of the differences between the three steps. For each comparison, there is a qualitative description of the probability of the standardised differences being larger than 0.02, followed by the size (standardised effect) and direction of the differences.
The differences in energy absorbed at the ankle (Figure 4.13) during the negative power phases of steps three (-0.027  $\pm$  0.007), nine (-0.050  $\pm$  0.010) and 19 (-0.078  $\pm$  0.020) were most likely large to very large. The energy generated during the positive power phases was 0.074  $\pm$  0.013, 0.075  $\pm$  0.013 and 0.081  $\pm$  0.017 during steps three, nine and 19, respectively. No clear differences were observed between steps three and nine, while the differences between steps nine and 19 were likely small. Throughout steps three, nine and 19, the ankle remained a net energy generator. The energy absorbed (A-) to energy generated (A+) ratio was 2.9  $\pm$  0.7 during step three, 1.5  $\pm$  0.2 during step nine and 1.1  $\pm$  0.2 during step 19.

#### 4.3.3.3 Knee Joint

Different angular patterns were observed at the knee between step three and steps nine and 19 (Figure 4.14a). In step three, the knee joint extended throughout the majority of stance, while during steps nine and 19, the knee joint flexed during the first half of stance before extending. Differences in touchdown knee joint angles between steps three  $(117 \pm 6^{\circ})$ , nine  $(142 \pm 6^{\circ})$  and 19  $(156 \pm 6^{\circ})$  were most likely very large. Knee flexion ROM was 0°,  $10 \pm 5^{\circ}$  and  $16 \pm 5^{\circ}$  during steps three, nine and 19, respectively. Differences between steps nine and 19 were most likely large. During the second half of stance, the differences in knee extension ROM (Figure 4.14a) were most likely very large between steps three  $(42 \pm 8^{\circ})$  and nine  $(25 \pm 9^{\circ})$  and most likely moderate between steps nine and 19 ( $17 \pm 6^{\circ}$ ). Differences in toe-off knee angle were likely small between steps three  $(159 \pm 6^{\circ})$  and nine  $(156 \pm 4^{\circ})$  and likely moderate between steps three and 19 ( $156 \pm 4^{\circ}$ ).

During step nine and 19, a knee flexor angular velocity was present which reached a peak  $0.035 \pm 0.015$  s ( $28 \pm 12\%$ ) and  $0.021 \pm 0.005$  s ( $20 \pm 5\%$ ) after touchdown, respectively. There was a most likely large increase in the knee flexor angular velocity between steps nine ( $-124 \pm 43$ ) and 19 ( $-202 \pm 60$ ). The peak knee extension angular velocity peaked at  $0.119 \pm 0.019$  s,  $0.100 \pm 0.019$  s and  $0.084 \pm 0.011$  s during steps three, nine and 19, respectively. There were no clear differences between the peak extensor angular velocities during steps three and nine.



**Figure 4.14.** Mean ± SD knee angle (a), normalised Knee angular velocity (b), normalised Knee moment (c) and normalised knee power between steps three (black), nine (blue) and 19 (red). The tables below the respective figures show the descriptive results of the results of the MBI analysis of the differences between the three steps. For each comparison, there is a qualitative description of the probability of the standardised differences being larger than 0.02, followed by the size (standardised effect) and direction of the differences.

Similar resultant knee moment patterns were observed between steps three, nine and 19 (Figure 4.14c). The joint moment was flexor dominant immediately after touchdown. The net knee moment then become extensor dominant throughout most of stance before becoming flexor dominant again before toe-off. At touchdown, the knee flexor moments were  $-0.04 \pm 0.03$  (step 3),  $-0.07 \pm 0.04$  (step 9) and  $-0.08 \pm$ 0.03 (step 19). The differences in knee flexor moment immediately following touchdown were very likely moderate between steps three and nine and most likely moderate between steps three and 19. The knee extensor moment peaked at 0.077  $\pm 0.020$  s (step three:  $50 \pm 16\%$ ),  $0.050 \pm 0.008$  s (step nine:  $41 \pm 6\%$ ) and  $0.045 \pm$ 0.005 s (step 19:  $43 \pm 8\%$ ). The peak knee extensor moment very likely moderately increased between steps three  $(0.09 \pm 0.02)$ , nine  $(0.12 \pm 0.03)$  and between steps three and 19 ( $0.12 \pm 0.05$ ).

During step three, immediately following touchdown and prior to toe-off the knee flexor moment absorbed energy (-0.004  $\pm$  0.004; Figure 4.15). During step nine and 19, the knee flexor moment generated energy immediately following touchdown (step 9: 0.001  $\pm$  0.001; step 19: 0.002  $\pm$  0.003) and absorbed energy before toe-off (step 9: -0.005  $\pm$  0.004; step 19 -0.002  $\pm$  0.002). Differences in total work done by the knee flexor moment (i.e. combined energy absorbed and generated by the resultant knee flexor joint moment) were unclear between steps three (0.004  $\pm$  0.004) and nine (0.005  $\pm$  0.004) and unclear between steps nine and 19 (0.005  $\pm$  0.004).

During step three, the mid-stance phase was dominated by a knee extensor power generation phase (0.023  $\pm$  0.011; Figure 4.15). During steps nine and 19 two knee power phases were observed during mid-stance. Firstly, the resultant knee extensor moment led to absorption of energy (step 9: -0.011  $\pm$  0.008; step 19: -0.016  $\pm$  0.011) while the knee flexed. Differences in negative work done by the knee extensor moment (Figure 4.15) was very likely moderate between steps nine and 19. Following this, the resultant knee extensor moment generated energy (step nine: 0.011  $\pm$  0.008; step 19: 0.006  $\pm$  0.004). The decrease in the energy generated by the knee extensors between steps three and nine was most likely large and likely small between steps nine to 19 (Figure 4.15). No clear differences in total work done by the resultant knee extensor moment (i.e. combined energy absorbed and

generated by the resultant knee extensor joint moment) between steps three (0.023  $\pm$  0.011) and nine (0.022  $\pm$  0.013) and between steps nine and 19 (0.022  $\pm$  0.014).



**Figure 4.15.** Mean  $\pm$  SD positive and negative knee work for steps three (black), nine (blue) and 19 (red). From left to right, the each cluster of bars represent knee flexor power generation (Kf+), knee extensor power absorption (Ke-), knee extensor power generation (Ke+) and knee flexor power absorption (Kf-). The table shows the results of the MBI analysis of the differences between the three steps. For each comparison, there is a qualitative description of the probability of the standardised differences being larger than 0.02, followed by the size (standardised effect) and direction of the differences.

## 4.3.3.4 Hip Joint

The hip joint extended throughout the stance phases of all three steps (Figure 4.16a). Differences in touchdown hip angles between steps three  $(100 \pm 9^{\circ})$ , nine  $(119 \pm 6^{\circ})$ , and 19  $(140 \pm 5^{\circ})$  were most likely very large to extremely large. Hip extension ROM decreases between steps three  $(73 \pm 6^{\circ})$  and nine  $(68 \pm 8^{\circ})$  were likely moderate and most likely moderate between steps nine and 19  $(60 \pm 6^{\circ})$ . Differences in toe-off hip angles were most likely large between steps three  $(173 \pm 10^{\circ})$  and step nine  $(187 \pm 7^{\circ})$  and most likely large between steps nine and step 19  $(200 \pm 4^{\circ})$ .



Figure 4.16. Mean ± SD hip angle (a), normalised Hip angular velocity (b), normalised hip moment (c) and normalised hip power between steps three (black), nine (blue) and 19 (red). The tables below the respective figures show the descriptive results of the results of the MBI analysis of the differences between the three steps. For each comparison, there is a qualitative description of the probability of the standardised differences being larger than 0.02, followed by the size (standardised effect) and direction of the differences.

A hip extensor angular velocity was observed through the stance phases of steps three, nine and 19 (Figure 4.16b). The hip extension angular velocity at touchdown was very likely moderately higher on step three  $(235 \pm 41)$  compared to steps nine  $(193 \pm 56)$  and very likely moderately higher on step three compared to step 19 (180  $\pm$  42). The differences in peak hip extension angular velocity between step three  $(317 \pm 31)$  and nine  $(368 \pm 38)$  were most likely moderate and were most likely large between steps three and 19  $(389 \pm 51)$ . Peak hip extensor angular velocity occurred at  $0.113 \pm 0.020$  s  $(72 \pm 8\%)$ ,  $0.093 \pm 0.013$  s  $(75 \pm 7\%)$  and  $0.077 \pm 0.014$  s  $(73 \pm 10\%)$  during steps three, nine and 19, respectively.

The increase in hip extensor moment at touchdown (Figure 4.16c) between steps three  $(0.11 \pm 0.04)$  and nine  $(0.21 \pm 0.07)$  was most likely large and between steps three and 19  $(0.19 \pm 0.06)$  was most likely moderate. A hip extensor moment was dominant at the beginning of stance and became flexor dominant at 0.115 ± 0.016 s  $(74 \pm 7\%)$  during step three,  $0.091 \pm 0.017$  s  $(74 \pm 9\%)$  during step nine and  $0.072 \pm 0.016$  s  $(68 \pm 11\%)$  during step 19. The peak hip extensor moment was  $0.20 \pm 0.03$  (step 3),  $0.24 \pm 0.04$  (step 9) and  $0.22 \pm 0.05$  (step 19) while the peak resultant hip flexor moments were  $-0.24 \pm 0.07$  (step 3),  $-0.24 \pm 0.08$  (step 9) and  $-0.24 \pm 0.09$  (step 19).



**Figure 4.17.** Mean ± SD normalised positive (H+) and negative (H-) hip work for steps three (black), nine (blue) and 19 (red). The table shows the results of the MBI analysis. The table shows the results of the MBI analysis of the differences between the three steps. For each comparison, there is a qualitative description of the probability of the standardised differences being larger than 0.02, followed by the size (standardised effect) and direction of the differences.

Largely owing to the angular velocity being extensor throughout, the hip power time-histories (Figure 4.16d) mostly mimicked the hip moment pattern. A positive

power phase was observed during the first two thirds of stance and the differences in the energy generated during this positive power phase were most likely large between steps three (0.10  $\pm$  0.03) and 19 (0.06  $\pm$  0.02) and between steps nine (0.09  $\pm$  0.02) and 19. During the last third of stance, a negative power phase was observed at the hip joint. No clear differences in energy absorbed were observed during the negative power phases of steps three (-0.04  $\pm$  0.02), nine (-0.04  $\pm$  0.02) and 19 (-0.04  $\pm$  0.02).

#### 4.3.4 Segment angles and angular velocities

The differences in touchdown rear foot angles (Figure 4.18g) were most likely large between steps three  $(132 \pm 9^{\circ})$  and nine  $(147 \pm 6^{\circ})$  and between steps three and 19  $(147 \pm 5^{\circ})$  compared to step. Following touchdown, the rear foot segment rotated in an anti-clockwise direction (direction of running left to right) as the segment angles increased up to  $137 \pm 9^{\circ}$  on step three,  $149 \pm 6^{\circ}$  on step nine and  $150 \pm 4^{\circ}$  on step 19. At toe-off, no clear differences in rear foot angles were observed between steps three  $(74 \pm 6^{\circ})$  and nine  $(75 \pm 6^{\circ})$  and likely small differences were observed between steps three steps nine and  $19 (79 \pm 6^{\circ})$ . Rear foot clockwise angular velocities peaked (Figure 4.18h) at  $0.146 \pm 0.015$  s  $(94 \pm 5\%)$  in steps three, at  $0.112 \pm 0.013$  s  $(91 \pm 6\%)$  in step nine and at  $0.088 \pm 0.013$  s  $(84 \pm 7\%)$  in step 19. The differences in peak clockwise rear foot angular velocities were likely small between steps three (-502 ± 83^{\circ}) and nine (-555 ± 76^{\circ}) and very likely moderate between steps nine and 19 (-630 ± 96^{\circ}).

Touchdown shank angles (Figure 4.18e) differences were most likely extremely large between steps three  $(63 \pm 5^{\circ})$  and nine  $(87 \pm 4^{\circ})$  and most likely very large between steps nine and 19 (97 ± 3°). The peak clockwise angular velocity (Figure 4.18f) increases were most likely large between step three (-146 ± 19) to step nine (-269 ± 75) and most likely moderate between step nine to 19 (-346 ± 86). At toe-off shank angles increases were very likely moderate between steps three (36 ± 4°) to nine (38 ± 3°) to 19 (41 ± 3°). Increases in shank ROM during stance were most likely very large between steps three (27 ± 6°) and nine (49 ± 5°) and most likely large between steps nine and 19 (56 ± 5°).



Figure 4.18. Mean segment angles across stance phases of steps three, nine and 19 (left) and mean segments angular velocities across steps three (black), nine (blue) and 19 (red).

Thigh angular velocity (Figure 4.18d) was clockwise (running direction left to right) throughout stance. At touchdown, differences in clockwise angular velocity were most likely moderate between steps three (-225  $\pm$  34) and nine (-188  $\pm$  36) and most likely large between steps three and 19 (-178  $\pm$  34). The clockwise angular velocity

peaked at 0.113  $\pm$  0.020 s (73  $\pm$  8% of stance) during step three, 0.091  $\pm$  0.011 s (74  $\pm$  5% of stance) during step nine and 0.079  $\pm$  0.015 s (74  $\pm$  9% of stance) during step 19. Differences in peak clockwise angular velocities of the thigh were very likely small between steps three (-264  $\pm$  57) and nine (-307  $\pm$  86) and between step three and 19 (-315  $\pm$  92). In contrast to the segments of the stance leg, the trunk orientation remained relatively consistent throughout the stance phases within the steps, but were clearly different (most likely very to extremely large differences) between steps three, nine and 19 (Figure 4.18a).

#### 4.4 Discussion

There is still a lack of understanding of the technical changes associated with a maximal sprint. Therefore, the aim of Theme 2 (Technique analysis) was to investigate the changes in joint kinetics between the initial acceleration, transition and maximal velocity phases. This will provide a new understanding of the changes in musculoskeletal characteristics as a sprint progresses, which will add valuable novel information to the body of knowledge of maximal sprinting. In order to address the aim of this chapter an IDA was undertaken to provide a full joint kinematic and kinetic analysis of the stance phases of steps three, nine and 19 within a group of sprinters. The discussion will focus on results that showed moderate to very large differences and range from likely to most likely meaningful. Where appropriate, mean  $\pm$  SD values will be presented to illustrate the average size of these differences.

The step characteristics presented for steps three, nine and 19 are similar to data previously presented in Chapter 3 and previous literature during the initial acceleration (Čoh et. al., 2006; Nagahara, Naito, Morin & Zushi, 2014; Nagahara, Matsubayashi et al., 2014; Debaere et al., 2013), transition (Hunter et al., 2004c; Yu et al., 2016; Chapter 3: Figure 3.7a) and maximal velocity phases Bezodis et al., 2008; Yu et al., 2016). Furthermore, the touchdown CM-h, trunk and shank angles (Table 4.3) as well as touchdown and toe-off distance (Table 4.4) in steps three, nine and 19 were similar to results previously reported for the initial acceleration, transition and maximal velocity phases in Chapter 3 of this thesis. The similarities of this data compared to previous research and Chapter 3 confirms the choice of steps three, nine and 19 as representative of steps in the initial acceleration,

transition and maximal velocity phases, respectively. The detailed kinetic analysis presented in this study will therefore increase understanding of the changing musculoskeletal demands as a maximal sprint progresses.

#### 4.4.1 Ground reaction force and impulse

The current investigation revealed that average and peak vertical forces (Figure 4.8) increased as step velocities (Table 4.2) increased between steps three, nine and 19. This supports previous research that have reported increasing stance average vertical force production as running velocities increase during increasing steady state running velocities (Weyand et al., 2000) and accelerated running (Nagahara et al., 2017a). Although average vertical force was not previously associated with acceleration performance (Rabita et al., 2015), higher average vertical forces have previously been associated with increased performance when running velocities are above 95% of maximal velocity (Nagahara et al., 2017a). Previously it has been shown that the maximal velocity phase is associated with a more inclined posture compared to previous phases (Clark & Weyand, 2014; Nagahara, Matsubayashi et al., 2014; Chapter 3). Here the more vertically orientated trunk, thigh and shank (Figure 4.18), and more extended knee and hip joints during steps nine and 19 could have contributed to the more vertically orientated GRF vector while the more horizontal foot segment will have resulted in more vertically orientated acceleration vector at the proximal and distal end points of the rear foot segment.

An asymmetrical vertical GRF curve is visible during step 19 compared to steps three and nine. This asymmetric vertical GRF curve, which is characterised by large magnitudes of force immediately following touchdown (Clark & Weyand, 2014), has previously been described as an important feature exhibited by sprinters when maximising maximal running velocity (Clark & Weyand, 2014). The large application of vertical GRF immediately following touchdown has previously been attributed to the large downward foot velocities immediately prior to touchdown, which result in large decelerations of the foot at touchdown (Clark & Weyand, 2014; Clark, Ryan & Weyand, 2017). Furthermore, the upright posture adopted by sprinters during maximal velocity sprinting contributes to the stiffness requirements needed to decelerate the body quickly following touchdown and therefore contributes to vertical force production (Clark & Weyand, 2014). In the current study, the more inclined shank and trunk (Table 4.3), more extended knee (Figure 4.14a) and hip (Figure 4.16a) angles at touchdown and larger absolute and relative downward foot velocities prior to touchdown (Table 4.4) could have contributed to the large increase in vertical GRF observed from step three to nine to 19. While differences in the joint moments between steps three, nine and 19 will have played a key role in generating the resulting GRF curves, the more upright posture and increasing downward foot velocities may have contributed to the differences in the early increase in vertical GRF following touchdown and also the earlier occurring vertical GRF peak identified during step 19.

Although the vertical impulse generated by sprinters is necessary to overcome gravity and prepare for the next flight phase, the relative horizontal impulse ultimately determines the acceleration of the sprinters. In the current study, the result that relative anterior-posterior impulse decreases as a sprint progresses (Table 4.6) is in line with previous research (Morin et al., 2015; Nagahara et al., 2016). The decrease in relative anterior-posterior impulse between steps three, nine and 19 resulted from an increase in relative braking impulses and decrease in relative propulsive impulses (Table 4.6). The increases in relative braking impulses were influenced by moderate to very large increases in the braking phase duration (step 3:  $0.012 \pm 0.005$  s; step 9:  $0.034 \pm 0.011$  s; step 19:  $0.043 \pm 0.008$  s) and large to very large increases in the peak braking forces (step 3:  $-0.4 \pm 0.3$  BW; step 9:  $-0.9 \pm 0.3$  BW; step 19:  $-1.2 \pm 0.3$  BW). On the other hand, decreases in relative propulsive impulses were due to moderate differences in peak propulsive forces between steps three and nine and very large to extremely large decreases in the duration of the propulsive phase (step 3:  $0.143 \pm 0.015$  s; step 9:  $0.089 \pm 0.004$  s; step 19:  $0.062 \pm 0.004$  s). Furthermore, no clear differences were identified between the peak propulsive forces measured on step nine and 19, which has also previously been reported by Yu et al. (2016). While the decrease in propulsive forces during a sprint may be inevitable due to the orientation of the sprinter becoming more inclined, the increasing relative braking impulses due to increases in both braking phase duration and braking force magnitude limit the anterior-posterior impulses generated by sprinters during the transition and maximal velocity phase. The braking phase therefore, may represent a potential area which sprinters can manipulate for performance gains (Figure 4.8b).

Previous literature has suggested that increases in sprinting performance could be achieved by minimising the braking forces generated during ground contact (Mann & Sprague, 1983; Mero, Komi & Gregor, 1992; Hay, 1994; Hunter et al., 2005). Specifically, it has been suggested that sprinters could minimise the braking forces by minimising the horizontal velocity of the foot immediately prior to touchdown (Mann & Sprague, 1983; Hay, 1994) as well as minimising touchdown distances (Hunter et al., 2005). Hunter et al. (2005) showed that during sprint acceleration, a smaller forwards horizontal foot velocity and small touchdown distances were associated with lower braking forces during a single step near the 16 m mark. In the current study, a similar trend was observed between horizontal foot velocity and relative braking impulses (Figure 4.9a) and between touchdown distances and relative braking impulses (Figure 4.9b). However, the relationships appear to be stronger in steps nine (which aligns with the step investigated by Hunter et al., 2015) and 19 compared to step three. Therefore, attempting to reduce braking impulses by minimising horizontal foot velocities or touchdown distances may be more beneficial during the transition and maximal velocity phases, which is when braking impulses start to play an important role in determining acceleration performance (Nagahara et al., 2017a). The link between horizontal foot velocities and braking impulses and between touchdown distances and braking impulses supports the hypothesis that minimising braking forces in sprinting could be achieved by minimising the touchdown distance and the horizontal velocity of the foot prior to touchdown (e.g. Mann & Sprague, 1983; Mero, Komi & Gregor, 1992; Hay, 1994; Hunter et al., 2005; Crick, 2013b). However, there is still a lack of empirical evidence quantifying the contributions to both the magnitudes and duration of braking forces during ground contact phases in sprinting.

The GRFs sprinters generate are governed by a constraint to balance the moments acting about the whole-body CM (Kugler & Janshen, 2010). Therefore, it could be speculated that a change in a single GRF component (e.g. braking forces) will result in a change in other GRF components to maintain postural stability. Interestingly, figure 4.9 shows that sprinters that had a negative horizontal foot velocity or touchdown distance on step three still produced a braking impulse, which suggests that these variables alone do not explain all braking impulse generated during

stance. Therefore, further investigation is required to understand how braking forces are generated.

## 4.4.2 Joint kinematics and kinetics

This section will consider the joint moments recorded in the current study in the context of those reported in previous sprinting research. However, since not all previous research has normalised their values in the same way, the values from previous studies were adjusted according to methods outlined in section 4.2.5 using the mean participant height and mass data presented in each individual study. Furthermore, when comparing data to previous research it is important also to consider differences in the running velocity, the phase of the sprint when data is being collected, whether the data was collected during a steady state, acceleration or deceleration sprint, the participants ability level and methodology used to process the data as these will also influence differences between studies. Bearing this in mind, the results from each joint will be discussed separately starting with the MTP joint.

# 4.4.2.1 MTP Joint

The MTP joint has previously not received much attention in the sprinting literature. However, Stefanyshyn and Nigg (1997) and Bezodis et al. (2012) have highlighted the that this joint is worthy of consideration as the joint moments about the MTP joint are similar in magnitude to those about the knee joint during the first step of a sprint. Furthermore, it has been suggested that performance during sprinting could be improved by minimising the energy absorbed at the MTP (e.g. Stefanyshyn & Nigg, 1997; Willwacher, König, Braunstein. Goldmann & Brüggemann, 2013). A plantar flexor moment about the MTP was observed throughout the stance phases of steps three, nine and 19 (Figure 4.10c). This was consistent with previous studies from step one (Bezodis et al., 2014), ~15 m into a sprint (Stefanyshyn & Nigg, 1997) and ~20 m into a sprint (Smith et al., 2014). Furthermore, the results of the current study were consistent with previous research (e.g. Stefanyshyn & Nigg, 1997; Smith et al., 2014; Bezodis et al., 2014) showing that the MTP joint is a large net energy absorber (Figure 4.11).

While the current study showed no clear differences in peak MTP moments between steps three, nine and 19, small to moderate increases in energy absorbed from steps three (normalised work: -0.013  $\pm$  0.005) to nine (normalised work: -0.018  $\pm$ 0.006) and step 19 (normalised work:  $-0.018 \pm 0.009$ ) were found. This was partly due to moderate to very large increases in the peak dorsiflexion angular velocity at the MTP joint between steps three, nine and 19 (Figure 4.10b). Previously Smith et al. (2014) showed MTP joint dorsiflexion and dorsiflexion angular velocities were significantly reduced while plantar flexor moments were increased when athletes wore sprint spikes versus barefoot conditions. This may be due to the increased bending stiffness associated with the sprint spikes compared to barefoot sprinting (Smith et al., 2014). In light of the results of Smith et al. (2014) it could be speculated that increasing longitudinal bending stiffness (LBS) may reduce the larger dorsiflexion ranges and larger dorsiflexion angular velocities reported for steps nine and 19 of the current study. It is however unclear how this will influence performance on an individual level, since Willwacher et al. (2013) identified two strategies when increasing LBS of running shoes. These include; increased ankle moments while maintaining ground contact times and decreased ankle moments with increased ground contact times. The latter of these may be detrimental to performance especially during maximal velocity sprinting when low ground contacts are important to maximise running velocities (Weyand et al., 2000). Among the four joints analysed in this study, it is clear that the MTP represents a unique joint in that multiple factors (e.g. biological structures of the foot and the stiffness of the shoe) potentially influence the resulting joint kinetics at that joint (Smith et al., 2014; Bezodis et al., 2012). Investigating the influence of these factors are beyond the scope of this thesis.

## 4.4.2.2 Ankle Joint

The kinematic and kinetic patterns at the ankle joint (Figure 4.12) were consistent between steps three, nine and 19 and with those previously reported in sprinting (e.g. Jacobs & van Ingen Schenau, 1992; Johnson & Buckley, 2001; Bezodis et al., 2008; Charalambous et al., 2012; Bezodis et al., 2014; Yu et al., 2016). In the current study, the resultant ankle moments, which were plantar flexor throughout stance, reached peaks of 0.18  $\pm$  0.02 (step 3), 0.21  $\pm$  0.03 (step 9) and 0.24  $\pm$  0.04 (step 19). These are quantitatively consistent with the corresponding values reported for the first stance (Charalambous et al., 2012:  $0.24 \pm 0.01$ ; Bezodis et al., 2014: 0.20 to 0.24), second stance (Jacobs & van Ingen Schenau, 1992: 0.17), transition phase (Johnson & Buckley, 2001: 0.27; Yu et al., 2016: 0.17) and maximal velocity phase (Bezodis et al., 2008: 0.25; Yu et al., 2016: 0.19).

Previous studies that have reported changes in joint kinetics over a range of steady state running velocities, either reported no increase in ankle moments as steady state running velocities increased (Belli et al., 2001; Kuitunen et al., 2002), or reported a 1.36 times increase in ankle moment at the lower running velocities (3.50 to 5.02 m·s<sup>-1</sup>) followed by no further prominent increases up to 8.95 m·s<sup>-1</sup> (Schache et al., 2011). These results are different to the results in this study, which highlighted that during accelerated sprinting moderate to large increases in peak ankle plantar flexor moments were observed between step three, nine and 19. The results of the current study show that an increasing ankle plantar flexor moment may be an important requirement of accelerated sprinting and therefore should be addressed in conditioning of the sprinter.

At the ankle joint, an energy absorption phase was immediately followed by an energy generation phase in all steps. When these changes in joint moment were combined with the increases in peak dorsiflexion angular velocities from steps three to nine to 19, a large increase in the energy absorbed at the ankle joint (Figure 4.13) was observed between steps three (-0.027  $\pm$  0.007) and nine (-0.050  $\pm$  0.010) and between steps nine and 19 (-0.078  $\pm$  0.020). These data suggest there is an increased requirement by the ankle plantar flexors to absorb the larger impact forces associated with sprinting during the transition and maximal velocity phases (Figure 4.8). The increase in energy absorbed at the ankle was achieved through a moderate increase in the dorsiflexion ROM between steps three and nine and a large increase in dorsiflexion ROM between steps nine and 19. This is consistent with data previously presented by Braunstein et al. (2013) comparing the first three steps from the initial acceleration phase to a step from the maximal velocity phase. Interestingly, when investigating the individual motion of the rear foot and shank segments, it becomes clear that the increased ROM was due to an increasing clockwise rotation of the shank (Figure 4.18). This may play an important role in absorbing larger vertical and larger braking forces associated with steps nine and 19. The increasing clockwise rotation observed at the shank between steps three to nine to 19 was probably due to an increasingly larger clockwise moment acting on the shank, which resulted from the GRF vector (Hunter et al., 2004c). This will have required a larger plantar flexor ankle moment to generate an anti-clockwise moment on the shank (Figure 4.12d), therefore preventing the collapse of the shank during initial ground contact (Hunter et al., 2004c).

During the second half of stance, increases in peak ankle power were small between steps three and nine, moderate between steps nine and 19 and large between steps three and 19. This was due to increases in both the ankle plantar flexion velocity (step 3:  $482 \pm 62$ ; step 9:  $510 \pm 66$ ; step 19:  $543 \pm 86$ ) and plantar flexor moment (step 3:  $0.13 \pm 0.01$ ; step 9:  $0.15 \pm 0.03$ ; step 19:  $0.16 \pm 0.03$ ). The larger ankle planter flexor moment on step nine and 19 compared to step three is probably representative of a release of energy stored in the elastic components surrounding the ankle during the negative power phase of the ankle (Cavagna, Komarek & Mazzoleni, 1971). Positive power generated by muscles is enhanced when preceded by a negative power phase during which the muscle tendon unit stretches (Cavagna et al., 1971). This may be an important mechanism to ensure the ankle remains a net energy generator as negative work at the ankle increases with increasing running velocities and could be achieved through an increased dorsiflexion ROM during the first half of stance (Figure 4.12a).

Although the energy absorbed at the ankle increased from steps three to nine to 19, the ankle joint remained a net energy generator. The ratio between energy absorbed (A-) to energy generated (A+) ratio was  $2.9 \pm 0.7$  in step three,  $1.5 \pm 0.2$  in step nine and  $1.1 \pm 0.2$  in step 19. The ratio in step three was similar to the 2.7 - 3.0 ratio presented by Bezodis et al. (2014) during the first step in sprinting. During maximal sprinting, data from Schache et al. (2011) also shows that the ankle remained a net energy generator with a ratio of 1.7 (A-: -0.020; A+: 0.035) during their fastest condition ( $8.95 \pm 0.7 \text{ m} \cdot \text{s}^{-1}$ ) however, Bezodis et al. (2008) previously reported that the ankle was a net energy absorber during the maximal velocity sprinting. The differences in results regarding the ankle work during the maximal velocity phase in this study compared to Bezodis et al. (2008) is probably due to the location were the measurements were taken. In the current study, step 19 occurred between 30.00 –

36.00 m into the sprint while in the study by Bezodis et al. (2008) data was collected at the 45 m mark of a sprint. Therefore, the participants in the current study may have been further from their steady state  $V_{max}$  compared to the participants investigated by Bezodis et al. (2008).

#### 4.4.2.3 Knee Joint

The knee joint shows the most notable differences between the steps compared to the other three joints. Over the first few steps of a sprint, the knee joint has previously been shown to extend throughout stance (Jacobs & van Ingen Schenau, 1992; Charalambous et al., 2012; Nagahara, Matsubayashi et al., 2014; Bezodis et al., 2014). This was also evident from the step three data of the current study (Figure 4.14a). During step nine, knee flexion ROM ( $10 \pm 5^{\circ}$ ) was observed at the start of stance, which increased up to step 19 ( $16 \pm 5^{\circ}$ ). Knee flexion following touchdown has previously been reported to start from the fourth step onwards (Nagahara, Matsubayashi et al., 2014) and has previously been reported during the transition (Hunter et al., 2004; Johnson & Buckley, 2001) and maximal velocity phases (Bezodis et al., 2008).

The knee patterns in this study revealed a resultant knee flexor moment during the initial and late stance phase and a knee extensor moment during mid-stance. Due to the matched filtering of kinematic and kinetic data (Bisseling & Hof, 2006; Bezodis et. al., 2013), no high frequency fluctuations in knee moments were observed during early stance for any step. A moderate increase in touchdown knee flexor moment from step three (-0.04  $\pm$  0.03) to nine (-0.07  $\pm$  0.04) and 19 (-0.08  $\pm$  0.03) was observed, which probably carried over from the terminal swing phase. Previously, Schache et al. (2011) reported that an increase in steady state running velocity was associated with an increase in knee flexor moment during the terminal swing phase. Also, increases in the negative work done by the knee flexors during the terminal steady state running (Schache et al., 2011) and accelerated sprinting (Nagahara et al., 2017). With the horizontal velocity of the foot prior to touchdown suggested to be an important determinant of braking forces (Hay, 1994), the knee flexor moment during the terminal swing phase could be an important contributor to minimising the

horizontal velocity of the foot relative to the CM immediately prior to touchdown (Table 4.4).

At touchdown, the moderate increase in knee flexor moment between steps three and nine was likely influenced by the very large increases in both CM-h and TD distances. This will have required a larger knee flexor moment to counter the extensor moment generated by the GRF vector passing anterior to the knee joint (Sun, Wei, Zhong, Fu, Li & Liu, 2015). A knee flexor moment that is present following touchdown could reflect an attempt to minimise braking forces by quickly moving their CM over the contact point (Mann & Sprague, 1980). The exact mechanism by which a knee flexor moment accelerated the CM over the contact point is still unclear, however, it could be speculated that a knee flexor moment accelerates the shank in a clockwise direction. Therefore, the knee flexor moments on steps three, nine and 19 could have contributed to the increase in the clockwise angular velocity of the shank between the steps (Figure 4.18f) which would have accelerated the knee forward over the contact point.

Within the same participants, the resultant knee extensor moment increased from step three  $(0.09 \pm 0.02)$  to step nine  $(0.12 \pm 0.03)$  and 19  $(0.12 \pm 0.05)$  (moderate positive differences). Disregarding initial high frequency fluctuations in knee moments observed in previous studies that processed their data for IDA using mismatched kinematic and kinetic cut-off frequencies, previously reported magnitudes of peak knee extension moments were 0.05 to 0.12 (Bezodis et al., 2014) and 0.06  $\pm$  0.01 (Charalambous et al., 2011) from step one, 0.10 from step two (Jacobs & van Ingen Schenau, 1992), 0.19 (Johnson & Buckley, 2001) and 0.10 (Yu et al., 2016) form the transition phase and 0.09 (Bezodis et al., 2008) and 0.12 (Yu et al., 2016) from the maximal velocity phase. Although the magnitudes of the peak knee extensor moments were comparable to some previous studies in sprinting (e.g. Jacobs & van Ingen Schenau, 1992; Bezodis et al., 2008; Bezodis et al., 2014; Yu et al., 2016) other studies have reported higher knee extensor moments ranging between 0.14 to 0.22 (e.g. Mann & Sprague, 1981; Belli et al., 2001; Johnson & Buckley, 2001; Kuitunen et al., 2002). Due to a number of reasons expressed earlier (e.g. participant ability, data processing methods), it is difficult to compare changes in knee kinetics across a sprint between different studies. A key strength of this research was that the same participants and methods were used to collect data from steps three, nine and 19 providing confidence that differences between steps represent true changes.

Previously, Belli et al. (2001) reported an increase in peak knee extensor moment from 0.14 to 0.22 as steady state running velocities increased between 4.00 m s<sup>-1</sup> to 8.90 m  $m s^{-1}$ . This is similar to the current findings showing an increase in peak knee extensor moments between steps three (5.81  $\pm$  0.24 m·s<sup>-1</sup>) and nine (8.36  $\pm$  0.46 m·s<sup>-1</sup>). However, no clear differences were identified between steps nine and 19 where running velocities increased between 8.36  $\pm$  0.46 m s<sup>-1</sup> and 9.67  $\pm$  0.58 m s<sup>-1</sup>. Previously Kuitunen et al. (2002) reported that knee extensor moments decreased from 0.22 to 0.17 as steady state running velocities increased between 70% to 100% of maximal velocity ( $\sim$ 7.00 to 9.73 m·s<sup>-1</sup>). The different results of the current study compared to the results reported by Kuitunen et al. (2002) may be explained by the differences in the task. While Kuitunen et al. (2002) collected data during steady state running trials, the participants in the current study were asked to accelerate maximally over the whole sprint. Therefore, findings from increasing steady state velocity studies cannot be directly transferred to increasing speeds during maximal effort accelerations. The current study therefore provides a new insight into maximal acceleration, where resultant knee extension moments initially increases between the initial acceleration and transition phases before plateauing up to the maximal velocity phase.

The moderate increase in peak knee extensor moment from step three to nine may have been a response to the large increase in downward velocity of the CM prior to touchdown (Table 4.2) combined with the orientation of the sprinters becoming more inclined (Table 4.3). A knee extensor moment generates an anti-clockwise rotation on the shank (Hunter et al., 2004c). The increase in knee extensor moment between steps three and nine may therefore be important to assist the ankle moment in preventing the collapse of the shank during stance and minimise the loss in CM-h during stance by minimising knee flexion (Johnson & Buckley, 2001). During step three, the negative vertical velocity of the CM (-0.24  $\pm$  0.13 m·s<sup>-1</sup>) was relatively small (due to short flight times) compared to steps nine (-0.52  $\pm$  0.17 m·s<sup>-1</sup>) and 19 (-0.69  $\pm$  0.11 m·s<sup>-1</sup>). The downward velocities of the CM and impact forces

associated with steps three were therefore small enough to ensure that the participants could extend their knee joint through stance. The knee extensor moment was therefore able to generate energy throughout most of the stance phase of step three ( $0.023 \pm 0.011$ ) therefore contributing to increasing horizontal velocity and CM-h throughout the majority of step three (Jacobs & van Ingen Schenau, 1992, Charalambous et al., 2012, Bezodis et al., 2014; Debaere et al., 2014).

During steps nine and 19, the downward CM velocity preceding touchdown and resulting impact forces at touchdown were large enough to result in knee flexion. In the current study, the increase in ankle moment, knee joint angle (Figure 4.14a) and only moderate increase in downward CM velocity prior to touchdown (Table 4.2) between steps nine and 19 may explain why further increases in knee extensor moments were not reported between steps nine and 19. Although the peak knee extensor moment showed no clear change between steps nine and 19, the energy absorbed in the presence of a resultant knee extensor moment increased moderately between steps nine (-0.011  $\pm$  0.008) and 19 (-0.016  $\pm$  0.011). A knee extensor moment may be important in maintaining CM-h (Johnson & Buckley, 2001). However, the knee extensor moment did not increase between steps nine and 19. Rather, the participants absorbed more energy at the knee through an increased knee flexion ROM. This may have important training implications to ensure that the knee extensors are properly conditioned to deal with the increasing requirements to perform negative work as velocities increase. This could be achieved using specific plyometric exercises or different version of the Olympic lifts, which emphasise absorption of energy at the knee.

Following the power absorption phase, the knee extensor moment possibly assisted with the increasing vertical and horizontal velocity of the CM (Mann, 1981) as energy was generated at the knee joint. Interestingly, when comparing the total work done at the knee while a resultant knee extensor moment was active no clear differences were identified between steps three ( $0.023 \pm 0.011$ ), nine ( $0.022 \pm 0.013$ ) and 19 ( $0.022 \pm 0.014$ ). This novel finding highlights that although the functional role of the knee extensor moment changes as the sprint progresses (i.e. from energy generation during step three to energy absorption followed by energy generation

during steps nine and 19), the capacity of the knee extensors to do work appears to remain unchanged.

#### 4.4.2.4 Hip Joint

The hip joint extended throughout the stance phases of steps three, nine and 19. Although Nagahara, Matsubayashi et al. (2014) showed that the total hip ROM (minimum flexion to maximum extension angle) increases up to step 14 before decreasing slightly up to step 25, the results of the current study revealed that during stance, moderate to large decreases in hip extension ROM were observed. Therefore, if total hip extension ROM increases as Nagahara, Matsubayashi et al. (2014) showed, then this probably results from an increase in hip extension ROM during the terminal swing phase. Interestingly, the stance ROM of the hip joint was shifted dorsally on later steps. This was due to a more extended touchdown and toe-off hip angles, due to the trunk angle being more 'upright' throughout during stance (Figure 4.18a). So although toe-off distance decreased (Table 4.4; Chapter 3: Figure 3.9) the hip angle at toe-off increased up to step 19. This may have important implications when it comes to selecting appropriate training exercises and will be addressed in section 4.4.4.

Although the hip angle was ultimately determined by the orientation of the trunk and thigh segments, the extension of the hip was due to the clockwise motion of the thigh that resulted in the hip extending throughout stance (Figure 4.18). A hip extensor moment directly influences the thigh and trunk segments by generating an anti-clockwise and clockwise motion at the trunk and thigh respectively. Although relatively large hip extensor moments were active early during the stance phases of steps three, nine and 19, the trunk angle remained relatively consistent throughout stance (Figure 4.18a). An anti-clockwise (running viewed from left to right) rotation of the trunk would have been prevented by the gravitational moment acting on the trunk as demonstrated by Bezodis (2009).

The relatively large hip extension velocities at touchdown suggests that the hip was extending prior to touchdown. The lower hip extension velocities at touchdown of steps nine 19 compared to step three suggests that the participants were not able to take advantage of the higher knee lift and longer flight times associated with sprinting at higher velocities to accelerate the leg down and back relative to the CM, and achieve a high hip extension velocity at touchdown. This was possibly due to an increased whole leg moment of inertia associated with more extended knee joint prior to ground contact of steps nine and 19. Despite the lower hip extension velocities of step nine and 19, the more extended leg prior to touchdown meant that the participants were able to achieve a larger tangential velocity of the foot (i.e. relative to the CM velocity) during steps nine and 19 compared to step three (Table 4.4).

The large increase in touchdown hip extension moments between steps three (0.11  $\pm$  0.04) and nine (0.21  $\pm$  0.07) and between steps three and 19 (0.19  $\pm$  0.06; Figure 4.16c) could be linked to the very large to extremely large increases in TD distance and CM-h between steps three and nine and between steps three and 19. As with the knee joint, an increasingly larger GRF vector will have passed anteriorly to the hip, which was counteracted by a hip extensor moment (Sun et al., 2015). The hip extension moment immediately following touchdown may be important to pull the CM over the contact point (Mann & Sprague, 1980), therefore minimising the braking impulse. Large knee flexor and hip extensor moments immediately following touchdown have previously been suggested to place sprinters at an increased risk of hamstring strain injuries (Mann & Sprague, 1980; Sun et al., 2015). From these results it could be speculated that during the transition and maximal velocity phase, sprinters are at an increasing risk of hamstring strain injuries due to the increasing demands placed on the hamstring muscle group to generate a sufficiently large knee flexor and hip extensor moments. This may play an important role during the transition phase where the smaller trunk inclination could result in an increased stretch of the biceps femoris long head and semimembranosus muscles and therefore an increase "elongation load" on the hamstring muscle group during ground contact (Higashihara, Nagano, Takahashi & Fukubayashi, 2015, p. 7).

The resultant hip moments were extensor dominant over the first 0.115  $\pm$  0.016 s (step 3), 0.091  $\pm$  0.017 s (step 9) and 0.072  $\pm$  0.016 s (step 19) of stance. The peak resultant hip extension moment magnitudes in this study were 0.20  $\pm$  0.03 (step 3), 0.24  $\pm$  0.04 (step 9) and 0.22  $\pm$  0.05 (step 19). The magnitudes of the hip extensor moment were similar to the corresponding adjusted values reported in previous

sprint research for the first step (Charalambous et al., 2012:  $0.20 \pm 0.01$ ; Bezodis et al., 2014: 0.13 - 0.17), steps of the transition phase (Yu et al., 2016: 0.24; Johnson & Buckley, 2001: 0.31) and the maximal velocity phase (Belli et al., 0.19  $\pm$  0.05; Kuitunen et al., 2002; 0.17; Bezodis et al., 2008: 0.19; Schache et al., 2011: 0.24; Yu et al., 2016: 0.26). The peak hip extensor moment moderately increased between steps three and nine. An increase in peak hip extensor moment has also been shown during steady state running research by Belli et al. (2001), Kuitunen et al. (2002) and Schache et al. (2011). However, the small decrease in peak hip extensor moments between steps nine and 19 may represent a trade-off between generating a maximal hip extension moment ensuring that the clockwise rotation of the thigh is sufficiently large without inducing a detrimental anti-clockwise rotation on the trunk segment (Bezodis, 2009) as the gravitational moment acting on the trunk decreases with increasing trunk angles.

The energy generated by the hip extensor moment decreased from steps three to nine to 19. This was due to the decreasing time over which a hip extensor moment was active between steps three, nine and 19 (large difference). This is different to results published from the terminal swing phase (e.g. Schache et al., 2011; Nagahara et al., 2017) which shows that there is an increase in the energy generated at the hip during the terminal swing phase. The time when the resultant hip moment became hip flexor dominant occurred at a similar instant to when the hip extensor angular velocity peaked. The peak extension angular velocity at the hip occurred at  $0.113 \pm 0.020$  s (step three; second peak),  $0.093 \pm 0.013$  s (step 9) and  $0.077 \pm 0.014$  s (step 19). The peak in hip extension angular velocity which aligns with the peak clockwise angular velocity of the thigh (Figure 4.18d), occurred at a time when the hip moment was relatively small. Since, all forces and moments acting on a segment influence its motion, further increases in hip extension velocity as the hip extensor moment decreased may have been due the knee extensor moment, which generates a clockwise rotation of the thigh segment (Hunter et al., 2004c).

After about two thirds of stance, the resultant hip joint moment became flexor dominant. This would have helped to decrease the hip extension angular velocity and control further hip extension as the hip approached its maximal range (Jacobs & van Ingen Schenau, 1992). A key performance indicator in elite sprinters is a reduction in the forward rotation of the thigh in an attempt to terminate hip extension as the hip approaches extension (Mann & Hermann, 1985). Bearing this in mind, the hip flexor moment plays an important role in decreasing the energy of the thigh in preparation for the next swing phase (Charalambous et al., 2012). However, this hip flexor joint moment may also play a further role preparing the sprinter for toe-off by rotating the upper body in a clockwise direction (Mann & Sprague, 1980). This would have helped to reduce the counter clockwise rotation of the trunk identified during the second half of stance (Figure 4.18b). Although the energy absorbed at the hip joint showed no clear differences between steps three, nine and 19 (Figure 4.17), studies investigating changes in joint kinetics during swing reported an increase in negative hip work during the initial swing phase (Schache et al., 2011; Nagahara et al., 2017). The decreasing hip work during stance reported in the current study and the increasing hip work during swing reported by Nagahara et al. (2017) suggests the main working range for the hip extensors change from stance to terminal swing as the sprint progresses. This change in hip joint function from stance to terminal flight phase may be an important characteristic of maximal sprint acceleration.

#### 4.4.3 Segment angles and angular velocities

During steps three, nine and 19 a proximal to distal timing of peak joint extension angular velocities and peak power was observed. The pattern where the peak angular extension and power at the hip (Figure 4.16 b & d) was followed by the knee (Figure 4.14 b & d) then the ankle (Figure 4.12 b & d) and finally the MTP joint (Figure 4.10 b & d) was consistent across all steps. This proximal-to-distal sequencing of joint extension patterns is associated with the action of bi-articular muscles and is thought to be related to a transfer of power to the more distal segments (Bobbert & van Ingen Schenau, 1988). Ultimately, the angular velocities of adjacent segments influence the joint angular velocity. Interestingly, the peak clockwise angular velocity of the thigh, rear foot and fore foot followed a proximal-to-distal sequencing in the timing of peak clockwise angular velocity (Figure 4.18). This was however not the case for the shank which reached a minimum value in clockwise angular velocity (Figure 4.18f) as the shank reached a relatively poor position to contribute to forward translation of the CM. A stable shank

segment may be important to maximise knee angular velocity and facilitate a transfer power from the thigh to the foot segment. The extension angular velocity of the hip, knee and ankle joint and the clockwise angular velocity of the thigh and rear foot segments peaked when the orientation of the thigh and foot segments were close to vertical (~90°; Figure 4.18) in all steps. This ensured that the linear velocity at the proximal endpoints of the segments had a relatively large horizontal component (Jacobs & van Ingen Schenau, 1992) ensuring maximal contribution to the horizontal velocity of the participants.

#### 4.4.4 Practical Implications

So far, the discussion has touched on a few practical implications that emerged from the findings of Theme 2. Previous research has shown that although the net anterior-posterior forces that sprinters generate decreases as a sprint progresses, an important characteristic of elite sprinters when compared to sub-elite sprinters is their ability to continue to generate large net anterior-posterior forces as a sprint progresses (Rabita et al., 2015). From the results of Theme 2 it could be inferred that while the moderate decreases propulsive forces are inevitable due to changes in the sprinters posture (Table 4.3), the large increases in braking forces and the duration of the braking phase represents a potential area which sprinters can manipulate for performance gains (Figure 4.8b). This was previously shown by Nagahara et al. (2017a), who reported that lower braking impulses are important to acceleration between 75% and 95% of maximal velocity. This corresponds to a distance on the track of about 7.5 m to 21.1 m (Nagahara et al., 2017a). By managing the step-to-step increases in the braking forces, sprinters could ensure that the step-to-step decreases in the net anterior-posterior forces are minimised as a sprint progresses. This aligns with the hypothesis that minimising braking forces in sprinting could be beneficial to performance (Mann & Sprague, 1983; Mero, Komi & Gregor, 1992; Hay, 1994; Hunter et al., 2005). Indeed, the results showed a positive trend between horizontal foot velocity prior to touchdown and braking impulse as well as the positive trend between touchdown distances and braking impulse, which were especially relevant during steps nine and 19. This supports previous suggestions that sprinters should attempt to minimise foot velocities prior to touchdown and decrease TD distances (Hay, 1994; Hunter et al., 2005). This could be achieved by emphasising an effective evolution of leg mechanics during the terminal swing and early contact phase. Specifically, it is suggested that during the terminal swing phase, sprinters should attempt to generate a high backward angular thigh velocity, which reduces foot velocity and TD distance and therefore results in smaller braking forces at touchdown (Seagrave, Mouchbahani & O'Donnell, 2009). Based on the results of the current study, sprinters are encouraged to manage between-step increases in touchdown distances and horizontal foot velocities through development of their 'front side mechanics' (Mann, 2007, p. 86). However, it must be noted that some amount of positive TD distance is probably needed to allow sprinters to generate a sufficient amount of vertical impulse (Young, 2006; Mann, 2007) during transition and maximal velocity phase sprinting.

Regarding changes in joint kinetics, the moderate increases in knee flexor moments between steps three, nine and 19 could have important implications to sprinters. A knee flexor moment immediately following touchdown is a characteristic that has also been reported in previous studies (e.g. Mann & Sprague, 1980; Johnson & Buckley, 2001; Bezodis et al., 2008; Bezodis et al., 2014) and is suggested to help reduce braking forces by accelerating the CM over the contact point (Mann & Sprague, 1980). However, an excessively large knee flexor moment combined with a relatively large hip extensor moment could be considered a risk factor for hamstring muscle strain (Sun et al., 2015). While it is beyond the scope of these results to suggest what can be considered excessive, coaches should be aware of these increasing knee flexor moments and should ensure that sprinters are physically prepared for this increased musculoskeletal demand. Furthermore, knee flexor moments are likely influenced by increases in TD distances (Sun et al., 2015) where large TD distances are expected to result in larger knee flexor moments. This may therefore be a further reason to ensure between-step increases in TD distances are managed.

The results of Theme 2 also highlighted the increasing demand by the ankle plantar flexors and knee extensor to absorb energy during stance as a sprint progresses. This is probably to maintain the height of CM (Johnson & Buckley, 2001) and stabilise the shank (Hunter et al., 2004c) during stance as running velocities increase. Subsequently, this could allow the power generated at the hip to be

transferred to the ankle (Johnson & Buckley, 2001). Interestingly, the results showed that the increasing ankle plantar flexor and knee extensor work was accompanied by an increased ROM over which energy was absorbed which resulted from an increased forward rotation of the shank relative to the motion of the thigh and foot segments. This may be important to consider when selecting exercises to train the plantar flexors and knee extensors to absorb energy. This could involve modified weight training exercises, specific plyometric drills that have a horizontal emphasis (Bosch & Klomp, 2005; Schiffer, 2009) or sprinting with added external load (Seagrave, 1996).

Finally, while previous research has shown that hip ROM (peak hip flexion to peak hip extension) increased (Nagahara, Matsubayashi et al., 2014) and the energy generated by the hip extensor during the terminal swing phase increased (Nagahara et al., 2017) as a sprint progresses, the results of Theme 2 showed during ground contact, hip extension ROM and the energy generated by the hip extensors decreased between steps three, nine and 19. Furthermore, the results of Theme 2 showed that during step 19, the hip joint was in a more extended position throughout ground contact when compared to steps three and nine. These findings may have important implications for training exercise selection. Specifically, when focusing on the ground contact phase of a sprint, coaches should consider selecting closedchain exercises that mimic the orientation of the thigh relative to the trunk while strengthening the hip extensors across the ranges observed during ground contact, while minimising the motion of the trunk. Furthermore, from findings of Theme 2 and the work of Nagahara et al. (2017), it could be inferred that the main function of the hip extensors shifts to the terminal swing phase as a sprint progresses. This capacity of the hip extensors to generate energy during the terminal swing phase should be addressed through the use of specific open chain activities. By ensuring that training is specific to the task, the carryover to the skill being developed could be maximised (Contreras, Cronin, Schoenfeld, Nates & Sonmez, 2013).

## 4.5 Conclusion

The research question posed in the introduction of this chapter asked how joint kinematics and kinetics change between steps in the initial acceleration, transition and maximal velocity phases. To answer this question, an IDA was undertaken. The

results showed some important between-step differences in ankle, knee and hip joints. Meaningful increases in ankle dorsiflexion and knee flexion ROM following touchdown as well as ankle plantar flexor and knee extensor moments were identified between steps three, nine and 19. This was probably a necessary response to allow the ankle and knee to absorb larger amounts of energy as the impact forces at higher running velocities increased. Furthermore, the increasing knee flexor and hip extensor moments at touchdown may have resulted from the increases in TD distances and CM-h. While the large hip extensor and knee flexor moments may have helped to reduce the braking forces experienced at higher velocities, larger hip extensor and knee flexor moments may predispose the hamstring muscles to a larger risk of injuries especially during the transition and maximal velocity phases. During the second half of stance and approaching toe-off, the joint kinematic and kinetic differences between the joints were less clear. This suggests that joint kinetics may not represent a limiting factor to generating net propulsive forces between steps three, nine and 19. Rather the increased demand to absorb the energy during the first half of stance and therefore manage the larger impact forces associated with high running velocities may play an important role in explaining the differences in external GRF observed over the first half of stance in the current and previous studies.

## 4.6 Chapter summary

The aim of Theme 2 (Technique analysis) was to investigate the changes in joint kinetics between the initial acceleration, transition and maximal velocity phases. The purpose provide a new understanding of the changes in musculoskeletal characteristics as a sprint progresses, which will add valuable novel information to the body of knowledge of maximal sprinting. Based on the results of Theme 1 (Chapter 3), steps three, nine and 19 were selected to investigate the differences between these phases in more detail. An IDA was used to provide a joint kinetic analysis on the stance phases of steps three, nine and 19 within a group of sprinters. To the author's knowledge, this is the first time that steps from across these phases have been directly compared in this manner within a population of experienced sprinters.

The results of this analysis revealed that the largest between-step differences occurred during the first half of stance while differences during the second half of stance were generally less clear. Specifically, during the first half of stance, the results revealed some important differences in joint moments and work at ankle and knee joints. This was possibly in response to larger impact forces (i.e. large vertical and braking GRF immediately following touchdown) and the need to decelerate the CM vertically at higher running velocities (Mann, 1981). Furthermore, the results from the current study and those previously publish by Nagahara et al. (2017) suggest that the decrease in energy generated at hip and knee during the terminal swing phase (Nagahara et al., 2017) and the increase and decrease in energy generated at the knee and hip respectively may be an important characteristic of maximal sprint acceleration.

While these results provide an important insight into the changing joint kinematic and kinetic aspects of technique in sprinting, the translation of the CM is ultimately dependent on the segment rotations generated by moment at the joints. Furthermore, due to dynamic coupling of the multi-articulated body, forces or joint moments acting on one segment can affect the acceleration all body segments (Zajac, 2002). The next step of this thesis will therefore investigate how the changing joint moments and segment orientations identified in this chapter influence the vertical and horizontal acceleration of the CM during steps three, nine and 19.

# **Chapter 5** – Induced acceleration analysis: Changes in contributions to performance

# 5.1 Introduction

Themes 1 and 2 highlighted some important differences between the initial acceleration, transition and maximal velocity phases of a sprint. Changes in posture (Theme 1) were associated with both an increase in CM-h and touchdown distance and a decrease in toe-off distance, as the sprinters' posture became more inclined. These changes in posture resulted from changes in segment orientations relative to the ground where shank angles at touchdown increased relatively quickly during the initial acceleration phase compared to the transition phase. Trunk angles increased throughout the initial acceleration and transition phases and plateaued during the maximal velocity phase. Chapter 4 demonstrated some meaningful differences in the joint kinetics associated with steps from the initial acceleration, transition and maximal velocity phase. These differences include increased peak ankle plantar flexor and knee extensor joint moments between steps three, nine and 19. These increased ankle plantar flexor and knee extensor moments were accompanied by increased ankle dorsiflexion and knee flexion angular velocities, which resulted in increased negative work done by the ankle plantar flexors and knee extensors between steps three, nine and 19. Since relative segmental orientations ultimately determine the direction of the CM acceleration while the magnitude of the joint moments dictate the size of the induced accelerations (Hof & Otten, 2005), the changes in posture and joint kinetics identified in Themes 3 and 4 both play and important role in generating the external GRF. Although the changes in external forces were characterised by increased peak braking forces and peak vertical forces from step three to step nine to step 19, it is difficult to intuitively predict the contributors to the changing ground reaction forces. Knowledge of these contributors could ultimately explain why certain training drills or technical cues are more appropriate than others are.

Contributions by joint moments and non-muscular forces (e.g. gravity and motion dependent forces) to whole-body CM acceleration have previously been investigated during walking (e.g. Hof & Otten, 2005; Kepple, Siegel & Stanhope, 1997; Pickle, Grabowski, Auyang & Silverman, 2016), running (e.g. Hamner, Seth

& Delp, 2010; Dorn, Schache & Pandy, 2012) and sprinting (e.g. Cabral et al., 2013; Debaere et al., 2015; Koike & Nagai, 2015). Studies that have investigated the contributions to CM acceleration during sprinting are generally in agreement that the plantar flexor moment at the ankle induces the largest forward and upwards acceleration on the CM (Cabral et al., 2013; Debaere et al., 2015; Koike & Nagai, 2015). However, given the changes in kinematics and joint kinetics throughout the acceleration phase, it is not known how the contributions to vertical and horizontal accelerations might change between different phases in sprinting. A comprehensive understanding of how induced accelerations change across the initial acceleration, transition and maximal velocity phases will provide understanding of the underlying mechanical determinants of maximal sprinting which are fundamental for informing training practice choices.

Considering the changes in segmental kinematics and joint kinetics associated with different phases of maximal sprinting, the research question v - What are the primary contributors to the acceleration of the CM during the initial acceleration, transition and maximal velocity phases? will be addressed to expand on the knowledge gained from Themes 3 and 4. Furthermore, in order to better understand how segment orientations and joint moments associate with specific ground reaction forces, a further research question iv - 'Why do the segmental accelerations induced by the different joint moments change between the initial acceleration, transition and maximal velocity phases?' will be addressed in this chapter. Using empirical data from Chapter 4, the aim of Theme 3 was to investigate the effects different forces (joint moments and non-biological) acting on a sprinter have on the sagittal plane acceleration of the sprinter during steps from different phases of a sprint. Using an Induced acceleration analysis (Theme 3), the purpose was to build on the knowledge gained from Themes 1 and 2 and develop a greater depth of knowledge regarding the underlying mechanisms by which sprinters accelerate their CM during steps during different phases of a sprint. This aim will be achieved by quantifying the contributions to segmental and whole-body CM accelerations using an induced acceleration analysis (IAA) (Zajac, 2002). The knowledge gained from this study will ultimately provide a better understanding of the link between technique and the performance of the sprinter and support coaches' and sport scientists' decision making during technique analysis and training specificity within the initial acceleration, transition and maximal velocity phases of sprinting.

## 5.2 Methods

## 5.2.1 Data Processing

The empirical GRFs and coordinate data from Theme 2 (Chapter 4; section 4.2.1) was used in the current study. As previously outlined in Theme 2 (Chapter 4; section 4.2.2) the videos from steps three, nine and 19 were digitised in Matlab (The MathWorks Inc., USA, version R2014a) using an 18 point model and reconstructed using a nine parameter 2D-DLT with lens correction. Kinematic data were filtered with a 4th order low pass Butterworth filter with a 26 Hz cut-off frequency. Data from de Leva (1996) were used to calculate the inertia data for all the segments except the foot. For the foot segments, data from Bezodis et al. (2014) was used with the mass of the sprint shoe added. Linear and angular segment velocities and accelerations were calculated using the three-point central differences method (Miller & Nelson, 1976). Ground contact was identified using a 10 N threshold in vertical GRF. The GRF data were down sampled to 200 Hz and filtered with a 4th order low pass Butterworth filter with a 26 Hz cut-off frequency. Joint moments were calculated according to Winter (2005), working from the ground up. The forefoot segment and MTP were included in the calculation when the centre of pressure (COP) was in front of the MTP joint (Stefanyshyn & Nigg, 1997).

#### 5.2.1.1 Induced acceleration analysis

Nomenclature fo	r induced acceleration analysis
А	Matrix of equations of motions (also see Appendix A5)
х	Vector of unknowns (also see Appendix A5)
С	Vector of known variables (also see Appendix A5)
F <sub>pi</sub>	Force at joint (at proximal joint of segment i)
F <sub>di</sub>	Force at joint (at distal joint of segment i)
$m_i$	Mass of i <sup>th</sup> segment
g	Acceleration due to gravity
a <sub>cmi</sub>	Acceleration of centre of mass of ith segment
a <sub>ct</sub>	Acceleration at the foot-floor contact point
$JM_{pi}$	Joint moment (at proximal joint of segment i)
JM <sub>di</sub>	Joint moment (at distal joint of segment i)

- $\ddot{\theta}_i$  Angular acceleration of ith segment
- $\dot{\theta}_i$  Angular velocity of i<sup>th</sup> segment
- $\vec{r}_{ip}$  (y or z) Position vector of centre of mass of segment i relative to proximal joint
- $\vec{r}_{id}$  (y or z) Position vector of centre of mass of segment i relative to distal joint

A two-dimensional IAA was performed in Matlab (The MathWorks Inc., USA, version R2014a) using an open source induced acceleration code (Hof & Otten, 2005, https://isbweb.org/software/movanal.html) which was adapted for the current study. These adaptations included: increasing the number of segments used to model the body to four, adjusting the definition of the contact constraints to include the multi-point foot-floor model described in section 5.2.1.2. For the current study, the model used in the IAA was based on a planar model of a sprinter and consisted of five segments: a fore foot, rear foot, shank, thigh, and a combined head, arms and trunk (HAT) segment. Kinematics and joint moments (JM) acting at the MTP, ankle, knee and hip joints which were calculated in Chapter 4 were used as inputs to the analysis. For this method, the Newton-Euler and constraint equations were written in matrix form (Hoff & Otten, 2005).

## $\mathbf{A} \times \mathbf{x} = \mathbf{c}$ [Equation 5.1]

Where A is a matrix represents the coefficients of the Newton-Euler equations of linear (Equation 5.2) and angular (Equation 5.4) motion as well as the constraint equations (equation 5.10 and 5.12). Also see appendix A5 for a complete illustration of matrix A. In matrix A rows 1 to 10 represent the equations for linear acceleration (Equation 5.2).

$$F_i - F_{i+1} + m_i g = m_i a_i$$
 [Equation 5.2]

Rows 11 to 18 represent the constraint equations (Equation 5.3) which ensure equal accelerations at the joints between segments.

$$\vec{a}_{cmi} + (\ddot{\theta}_i \times \vec{r}_{ip}) - (\dot{\theta}_i^2 \times \vec{r}_{ip}) = \vec{a}_{cm(i+1)} + (\ddot{\theta}_{(i+1)} \times \vec{r}_{(i+1)d}) - (\dot{\theta}_{(i+1)}^2 \times \vec{r}_{(i+1)d})$$
[Equation 5.3]

Rows 19 to 24 represent the equations of angular acceleration (Equation 5.4).

$$(F_{di} \times r_{id}) - (F_{pi} \times r_{ip}) + JM_{dj} - JM_{pj} = I_i \times \ddot{\theta}_i$$
 [Equation 5.4]

Rows 25 to 27 represent the contact equations with the ground (Equation 5.5) which describe the accelerations at the contact point of the system.

$$ac = a_{cm1} + \ddot{\theta}_1(r_{1d}) - \dot{\theta}_1^2(r_{1d})$$
 [Equation 5.5]

Vector c is a 27 x 1 column vector containing the known variables from equations 5.9 - 5.12 (see also appendix A5). Rows 1 – 10 include known external forces acting on segments 1 to 5. For this study, these external forces included the effect of gravity and the force exerted by the swing leg on the HAT segment. The forces at the hip joint of the swing leg were determined by performing an IDA by working from the most distal segment (i.e. foot) and working up to the proximal segment (i.e. thigh). Rows 11 to 18 include the variables of the centripetal accelerations (CA) of the MTP, ankle, knee and hip joints. These use the known angular velocities of the segments as inputs to equation 5.3 above. Rows 19 to 23 of vector c contain the known joint moments (JM) of the MTP, ankle, knee and hip. Each joint moment acts on the proximal end (+JM) the distal segment and on the distal end (-JM) of the rear foot and on the distal end of the shank. Finally, rows 24 to 27 include the known accelerations (ac<sub>x</sub>, ac<sub>y</sub>) at the contact point with the ground (Otten, 2003). These accelerations at the contact point were calculated according to equation 5.5.

Vector x is a 1 × 27 column vector of unknowns. From top to bottom, this vector consists of: the unknown y and z components of the intersegmental forces at the MTP, ankle, knee and hip (rows 1 -8); the unknown y and z components of the linear accelerations of the fore foot, rear foot, shank, thigh and HAT segments (rows 9 – 18); the unknown angular accelerations of the fore foot, rear foot, shank, thigh and HAT segments (rows 19 – 23) and the unknown y and z components of the ground reaction forces (rows 24 – 27) induced by individual inputs from vector c. By inverting matrix A the equation can be solved for the unknown vector x (Equation 5.6).

 $\mathbf{x} = \mathbf{A}^{-1} \ \times \mathbf{c}$ 

[Equation 5.6]

## 5.2.1.2 Contact model

At the start and end of ground contact, when either the MTP or distal hallux (toe) was above a vertical position threshold (see next paragraph) the foot-floor

interaction was modelled at a single contact point. The foot-floor interaction was defined as a 1 degree of freedom revolute joint between the instantaneous COP and the CM either of the rear foot or between the COP and MTP joint. As was the case for calculating joint moments of the MTP joint (Chapter 4; see section 4.2.4), when the COP was behind the MTP joint, the CM rear foot segment was connected to the COP. On the other hand, while the COP was in front of the MTP joint, the CM of the forefoot segment was connected COP. While the single point contact model was used, the coefficients of the contact joint were entered in rows and columns 24 to 25 of matrix A while the acceleration at the contact point (Equation 5.5) were entered into rows 24 and 25 of vector c. The calculated GRF was therefore simply the vertical and horizontal forces calculated at the single contact point (rows 24 and 25 of vector x).

During 'mid-stance', two different multi-point contact models were used depending on whether the MTP and toe were grounded. Two vertical displacement thresholds, which were 0.01 m above the lowest vertical positions reached by the MTP and toe coordinates, were used to identify when the MTP and toe were grounded. This would account for any surface and soft tissue deformation that would occur during ground contact. The first multi-point model was applied when 1) the COP was in front of the MTP joint, 2) the MTP joint was below its vertical threshold and 3) the toe was above its vertical threshold. When these conditions were met, the multi-point contact model was defined at the horizontal location of the MTP and at the instantaneous COP. In this case, the centre of mass of the forefoot was connected to the MTP contact point and to the instantaneous COP. The second multi-point model was used when 1) the COP was in front of the MTP joint, 2) the MTP was below the vertical threshold and 3) the toe was below the vertical threshold. With the second multi-point model, contact was defined at the horizontal locations of the MTP and toe. In this case, the centre of mass of the forefoot was connected to the MTP contact point and to the toe contact point. When the two-point contact models were used, the coefficients of the contact points at the MTP contact point were entered in rows and columns 24 to 25 of matrix A and the accelerations at the MTP contact point were inserted in the rows 24 to 25 of vector c. The coefficients relating to the COP or toe contact point were entered into rows and columns 26 to 27 of matrix A while the accelerations at the COP or toe contact point were inserted into rows 24 to 25 of vector c. Finally, the total vertical and horizontal GRFs were calculated as the sum of the horizontal and vertical forces calculated from the MTP and toe contact points (rows 24 to 27 of vector x).

# 5.2.1.3 Performing the IAA

To identify the individual contributions, the induced accelerations resulting from the joint moments, gravity and centripetal accelerations were solved separately. The intersegmental forces, induced accelerations and induced ground reaction forces were solved using the following procedure:

- 1. Kinematic data (positons of segment end-points and entre of masses) and inertial data (segment masses and moments of inertia) were used as inputs to set-up matrix A for all instances of ground contact.
  - After filling matrix A with the necessary coefficients (see appendix A5) the remap function was used to create a 27×27×k matrix (k= number of ground contact frames)
- Vector c was created by inserting the inputs separately. In other words, a 27×k matrix for each of the inputs (i.e. gravity, centripetal accelerations at the joints, individual joint moments, accelerations at the contact point and the forces exerted by the swing leg on the trunk) was created.
- Matrix A was then inverted using the pseudo inverse function in Matlab.
- 4. Matrix  $A^{-1}$  was then multiplied by the vector c.
- 5. Finally, all individual contributions were summed to calculate the total induced acceleration.

The accuracy of the model was assessed according to the superposition principle (Anderson & Pandy, 2003; Latash, 2008). Superposition implies that the total output of a system is equal to the sum of the outputs produced by each individual input separately (Latash, 2008). This means for the results of the IAA to be perfectly accurate, the total induced CM accelerations calculated in step 5 above should be equal to the empirically measured CM accelerations (using the GRF data). The agreement between the calculated and measured CM acceleration was determined by computing the RMSD (across stance) between the measured and total induced
horizontal and vertical ground reaction forces calculated by the IAA. These vertical and horizontal RMSD's were also expressed as a percentage of the total vertical and horizontal force excursion, respectively, as is common when evaluating the accuracy of ground contact models (e.g. Yeadon & King, 2002; Wilson, King, & Yeadon, 2006; Bezodis et al., 2015).

To investigate the contribution of each input to changes in CM velocity, the induced CM accelerations calculated for each input were integrated (trapezium rule) with respect to time. While the induced vertical GRF were integrated across the entire stance phase, the induced horizontal forces were split into those occurring during the braking phase of ground contact and those occurring during the propulsive phase of ground contact. The braking and propulsive phases of each ground contact were determined from the total induced horizontal GRF data. All impulses are presented relative to body mass.

## 5.2.1.4 Induced power analysis

To identify whether the segmental accelerations induced by the joint moments are either increasing or decreasing the energy of a segment, the previously calculated induced accelerations by the different joint moments were used as inputs to perform an induced power analysis (IPA). The energy delivered to each of the HAT and LEG (fore foot, rear foot, shank and thigh combined) were quantified to understand how different joint moments influenced the current state of the system. This means if the accelerations induced on a segment acted in the same direction as the velocity vector, the energy was increased (i.e. the HAT or LEG was accelerated) by the joint moment. On the other hand, if the acceleration induced acted in the opposite direction to the velocity, the energy was decreased (i.e. the HAT or LEG was decelerated) by the joint moment. For the purpose of this study the horizontal and vertical induced powers were calculated.

## 5.2.2 Data presentation

To present discrete induced acceleration data for each step, the data for each participant was averaged across the stance phase for each of their three steps. The data for each step was then averaged across participants to create an ensemble mean for each step. When presenting group means of continuous data for each step, the time-history data for each participant was first time nominalised to 101 data points. The data was then averaged across the participants to create an ensemble mean for each step. The mean continuous data for each step was presented relative to the mean contact time for each step. To address the research question v which aimed to understand contributions to CM accelerations during steps three, nine and 19, all contributions will initially be included in the analysis. These will initially include all contribution (i.e. contributions by all joint moments, by the foot-floor accelerations (Equation 5.5), the contributions by the centripetal accelerations of the joints of the stance leg (Equation 5.3) and the forces exerted on the HAT segment by the swing leg). Then the analysis will focus on the contribution by each joint moment individually (i.e. MTP, ankle, knee and hip moments).

### 5.2.2.1 Force events

To address research question iv which aims to understand how individual joint moments generated the GRFs, three peak force events present in all three steps were selected to analyse how different joint moments induced accelerations on the different segments within the IAA model. These events, which were expressed in percentage of stance, include the instants when peak braking, peak vertical and peak propulsive forces occurred. The kinematic, induced acceleration and induced power data associated with those instantaneous events were then identified. After the relevant data at each force event were identified for each participant's three steps, the data were averaged across participants to create an ensemble mean for each force event of steps three, nine and 19. This was used to create a representative stick figure diagram for each of those force events. An example is shown in figure 5.1.

In the results section, one complete figure for each force event will be presented for each step. These figures will be accompanied by the corresponding joint moment and induced CM acceleration data to assist interpretation of the figure while taking into account the joint moment and segment orientation data. In addition, when describing segment rotations as either clockwise or anti-clockwise, this will always be relative to the direction of motion being from left to right. As an example, the hip moment data in figure 5.1 could be interpreted in the following way: *At the time of the peak braking force event of step 19 (~9% of stance) the hip moment exhibited* 

an extensor joint moment of 0.14 (dimension less). The linear and angular accelerations induced on the segments of the model were as follows: a backward and downward linear acceleration and an anti-clockwise angular acceleration was induced on the rear foot and shank. A backward and downward linear acceleration and a clockwise angular acceleration was induced on the thigh segment. The linear acceleration induced on the rear foot, shank and thigh decreased the horizontal energy and increased the vertical energy of the LEG. This means that the horizontal accelerations induced on the segments of the LEG were opposite to the direction of the velocity vector of the LEG while the vertical accelerations induced on the LEG were in the same direction as the velocity vector of the LEG. The hip extensor moment induced a relatively small upward and forward acceleration on the HAT segment. The linear accelerations induced on the HAT increased the horizontal energy and decreased the vertical energy of the HAT. This means that the hip extensor moment also accelerated the HAT forwards and the HAT downwards.



**Figure 5.1.** Orienation of the fore foot, rear foot, shank, thigh and HAT at the instants of peak braking force during step 19. The arrows indicate the contribution of the MTP and ankle (purple), knee (blue), hip (red) and total (black) joint moments on segment accelerations during steps three, nine and 19. The induced CM acceleration is represented by the light grey arrow. Below the figures, the joint moments, induced CM accelerations and segment orientations corresponding to the peak braking force event percentage of stance shown top left corner of each figure). The segments, coloured arrows and ground reaction force vectors are to scale. See text boxes for a description of the figure/table.

## 5.2.3 Data analysis

Descriptive statistics (ensemble mean  $\pm$  SD) were calculated from the stance averaged and time normalised induced GRF and acceleration data for each participant. The meaningfulness of the differences between the discrete induced acceleration data from steps three, nine and 19, were quantified using MBI (Batterham & Hopkins, 2006; also see Chapter 4: section 4.2.7). Differences between means (step: 9-3; 19-3; 19-9) were calculated using the post-only crossover (Hopkins, 2006) with a confidence interval (after adjusting for the number of comparisons, three) of 97%. The smallest worthwhile change was set at an effect size of 0.2 (Hopkins, 2004; Winter et al., 2014). The mechanistic inference was used to quantify whether the differences were either positive, trivial or negative and the probability (% and qualitative description) that the differences were bigger than 0.2 was defined by: very unlikely: <5%; unlikely: 5% - 25%; possibly 25 - 75%; likely: 75% - 95%; very likely: 95% - 99.5% and most likely >99.5% (Hopkins et al., 2009). When the outcome of the effect had a >5% chance of being positive and negative, the mechanistic outcome was described as unclear. The magnitude of the observed differences (effect sizes), were quantified using the following scale: 0.0 (trivial), 0.2 - 0.59 (small), 0.6 - 1.19 (moderate), 1.2 - 1.99 (large), 2.0 - 3.99 (very large) and >4.0 (extremely large; Hopkins et al., 2009).

# 5.3 Results

## 5.3.1 Accuracy

The accuracy of the IAA shown in table 5.1 and figure 5.2. Relative errors of  $1 \pm 0$  to  $3 \pm 1\%$  of the horizontal and vertical force excursion were determined.

the sum vertical and norizontal induced ground reaction forces calculated from all inputs.						
	Step 3		Step 9		Step 19	
RMSD	Absolute	Relative	Absolute	Relative	Absolute	Relative
	[N]	[%]	[N]	[%]	[N]	[%]
Horizontal	11 ± 2	2 ± 0	17 ± 4	2 ± 1	33 ± 11	3 ± 1
Vertical	17 ± 6	1 ± 0	23 ± 9	1 ± 0	34 ± 11	1 ± 1

**Table 5.1.** Absolute and relative RMSD between the measured vertical and horizontal forces and the sum vertical and horizontal induced ground reaction forces calculated from all inputs.

## 5.3.2 Induced CM accelerations

Initially all contributions were included in the analysis. These include the joint moments, foot-floor accelerations, centripetal accelerations of the joints of the stance leg and forces exerted on the HAT by the swing leg. The joint moments

induced the largest horizontal and vertical CM acceleration. Peak vertical accelerations (Table 5.2) induced by the joint moments increases were most likely very to extremely large between steps three, nine and 19. No clear differences were found for the vertical impulse induced by the joint moments (Table 5.2). The differences in relative impulses (Table 5.2) induced by the joint moments during the braking phase of ground contact were very likely moderate between steps three and nine and most likely very large between steps nine and 19. Differences in impulses (Table 5.2) induced by the joint moments during the propulsive phase of ground contact were most likely extremely large between steps three and nine and most likely very large between steps nine and 19.

<b>Table 5.2.</b> Mean ± SD peak accelerations and relative impulses induced by the joint moments.								
		Step 3	Step 9	Step 19				
Peak induced accelerations:		•	•	•				
Backward	[m·s <sup>-2</sup> ]	-0.04 ± 0.35	-1.60 ± 1.15	-4.19 ± 0.90				
Vertical	[m·s <sup>-2</sup> ]	22.40 ± 1.95	28.68 ± 2.98	35.22 ± 2.95				
Forward	[m⋅s <sup>-2</sup> ]	8.97 ± 0.95	$7.66 \pm 0.90$	6.91 ± 0.78				
JM relative impulse contribution to:								
Braking phase	[m⋅s⁻¹]	0.01 ± 0.01	-0.03 ± 0.04	-0.11 ± 0.03				
Vertical impulse	[m⋅s⁻¹]	0.60 ± 0.14	0.94 ± 0.17	1.14 ± 0.14				
Propulsive phase	[m⋅s⁻¹]	0.78 ± 0.04	0.37 ± 0.03	$0.26 \pm 0.03$				

There was a large contribution by the accelerations at the foot-floor joint to the braking force and vertical force during initial ground contact (0.00 - 0.02 s) (Figure 5.2). The peak backward induced CM accelerations (and relative horizontal impulse) due to the accelerations at the foot-floor interface were  $-1.41 \pm 0.82 \text{ m} \cdot \text{s}^{-2}$  (-0.01 ± 0.01 m·s<sup>-1</sup>) on step three to -3.66  $\pm$  1.13 m·s<sup>-2</sup> (-0.05  $\pm$  0.01 m·s<sup>-1</sup>) on step nine to  $-5.72 \pm 1.11 \text{ m} \cdot \text{s}^{-2}$  (-0.08 ± 0.02 m  $\cdot \text{s}^{-1}$ ) on step 19. The differences in backward induced CM accelerations were most likely large between steps nine and 19. The backward accelerations induced by the accelerations at foot-floor joint contributed 145% (step 3), 68% (step 9) and 47% (step 19) of the total braking impulse with the horizontal deceleration of the rear/fore foot segment at touchdown contributing 125%, 101% and 101% of the impulse induced by the total foot-floor accelerations during steps three, nine and 19 respectively. The upward impulse generated by the upward induced accelerations due to the accelerations at the foot-floor joint were  $0.08 \pm 0.02 \text{ m} \cdot \text{s}^{-1}$  (step 3) to  $0.10 \pm 0.03 \text{ m} \cdot \text{s}^{-1}$  (step 9) to  $0.14 \pm 0.04 \text{ m} \cdot \text{s}^{-1}$  (step 19) which contributed 3% (step 3), 5% (step 9) and 6% (step 19) of the total vertical



impulse. The differences between steps three and nine and between nine and 19 were most likely moderate and most likely large, respectively.

**Figure 5.2.** The horizontal and vertical induced GRF (and centre of mass accelerations) due to the joint moments (round dot line), gravity (square dot line), joint centripetal acceleration (CA; dashed line), foot-floor accelerations (dash dot line) and the contralateral leg (long dash line). The total calculated (sum of all inputs; solid line) and measured GRF (grey shaded area) are also presented. Data for step three (a & b), nine (c & d) and 19 (e & f) is presented.

The differences in relative anterior-posterior impulse induced by the centripetal accelerations at the joints of the stance leg, which are calculated from the segmental angular velocities, were most likely meaningful moderate between steps three (0.01  $\pm$  0.01 m·s<sup>-1</sup>) to nine (0.03  $\pm$  0.01 m·s<sup>-1</sup>) and most likely large between steps nine and 19 (0.05  $\pm$  0.01 m·s<sup>-1</sup>). This input contributed 1% (step 3), 10% (step 9) and 57% (step 19) on the total horizontal impulse of the step. The relative vertical

impulse induced by the centripetal accelerations at the joint contributed -3% (step 3), -4% (step 9) and -6% (step 19) of the total vertical impulse.

Gravity induced a downward acceleration of -9.63 m·s<sup>-2</sup> (step three), -9.64 m·s<sup>-2</sup> (step nine) and -9.63 m·s<sup>-2</sup> (step 19) on the CM. The induced accelerations due to skeletal alignment (9.81 minus the induced accelerations due to gravity), which is the body's resistance to gravity due to the alignment of the segments (Liu, Anderson, Schwartz and Delp, 2008) was 0.18 m·s<sup>-2</sup> (step 3), 0.17 m·s<sup>-2</sup> (step 9) and 0.18 m·s<sup>-2</sup> (step 19).

## 5.3.3 Contribution by joint moments

#### 5.3.3.1 Foot complex

The MTP moments joint induced small downward and backward acceleration on the CM throughout the majority of ground contact (Figure 5.3 & Figure 5.4). The ankle plantar flexor moment induced large upward and forward accelerations on the CM throughout the majority of ground contact during steps three, nine and 19 (Figure 5.3 & Figure 5.4). Differences in the peak backward horizontal accelerations induced by the ankle plantar flexor moment were likely small between steps three (-0.11 ± 0.32 m s<sup>-2</sup>) and nine (-0.56  $\pm$  0.74 m s<sup>-2</sup>) and very likely moderate between steps nine and 19 (-2.52  $\pm$  1.16 m s<sup>-2</sup>). Increases in backward directed impulses resulting from the backward induced CM accelerations were likely small between steps three  $(0.00 \pm 0.00 \text{ m} \cdot \text{s}^{-1})$  to nine (-0.01 ± 0.01 m \cdot \text{s}^{-1}) and most likely very large between steps nine and 19 (-0.04  $\pm$  0.02 m·s<sup>-1</sup>). Differences in peak forward accelerations induced by the ankle moment were likely small between steps three (12.55  $\pm$  1.17  $m \cdot s^{-2}$ ) and nine (11.86 ± 1.40  $m \cdot s^{-2}$ ) and very likely moderate between steps nine and 19 (10.88  $\pm$  1.37 m·s<sup>-2</sup>). The differences in the forward impulses (Table 5.3) induced on the CM by the ankle moment were most likely very large between steps three and nine and most likely large between steps nine and 19. Differences in peak vertical accelerations induced by the ankle plantar flexor moment most likely large between steps three (19.85  $\pm$  1.92 m·s<sup>-2</sup>) and nine (26.31  $\pm$  2.95 m·s<sup>-2</sup>) and most likely large between steps nine and 19 (31.78  $\pm$  4.07 m·s<sup>-2</sup>).



**Figure 5.3.** Total and individual induced horizontal and vertical ground reaction forces (and centre of mass accelerations) due the joint moments. The measured ground reaction forces (shaded area) is also presented as a reference. Data for step three (a & b), nine (c & d) and 19 (e & f) is presented.

## 5.3.3.3 Knee

The knee flexor moment induced forward and downward acceleration on the CM during the first 0.02 s of stance (Figure 5.3). The differences in peak forward CM acceleration induced by the knee flexor moment at touchdown was most likely large between steps three (0.93  $\pm$  0.47 m·s<sup>-2</sup>) and nine (2.50  $\pm$  0.90 m·s<sup>-2</sup>) and most likely

very large between steps three and 19 ( $3.10 \pm 0.85 \text{ m} \cdot \text{s}^{-2}$ ). The knee flexor moment induced a forward impulse on the CM during the braking phase of stance (Table 5.3). Differences in forward impulse induced on the CM by the knee flexor moment were most likely moderate between steps three ( $0.00 \pm 0.01 \text{ m} \cdot \text{s}^{-1}$ ) and nine ( $0.02 \pm 0.02 \text{ m} \cdot \text{s}^{-1}$ ), and most likely large between steps three and 19 ( $0.03 \pm 0.02 \text{ m} \cdot \text{s}^{-1}$ ).

The knee extensor moment induced backward and upward accelerations. Differences in peak backward induced CM acceleration were most likely large between steps three ( $-2.63 \pm 0.68 \text{ m} \cdot \text{s}^{-2}$ ) and nine ( $-4.41 \pm 1.01 \text{ m} \cdot \text{s}^{-2}$ ) and between steps three and 19 ( $-4.93 \pm 1.91 \text{ m} \cdot \text{s}^{-2}$ ). Differences in the peak vertical CM accelerations induced by the knee extensor moment were likely small between steps three ( $3.18 \pm 0.92 \text{ m} \cdot \text{s}^{-2}$ ) and nine ( $3.86 \pm 1.26 \text{ m} \cdot \text{s}^{-2}$ ) and unclear between steps nine and 19 ( $3.94 \pm 1.66 \text{ m} \cdot \text{s}^{-2}$ ).

## 5.3.3.4 Hip

The hip moment induced relatively small accelerations on the CM. A hip extensor moment induced a backward and downward acceleration on the CM while a hip flexor moment induced a forward and downward acceleration on the CM (Figure 5.3 & Figure 5.4).

Table 5.3. Group mean ± SD relative impulses induced by each of the joint moments.							
		Step 3	Step 9	Step 19			
MTP:							
Backward	[m·s <sup>-1</sup> ]	-0.20 ± 0.09	-0.16 ± 0.07	-0.12 ± 0.06			
Vertical	[m·s <sup>-1</sup> ]	-0.06 ± 0.08	-0.01 ± 0.06	-0.03 ± 0.07			
Forward	[m⋅s⁻¹]	$0.00 \pm 0.00$	$0.00 \pm 0.00$	$0.00 \pm 0.00$			
Ankle:							
Backward	[m⋅s⁻¹]	$0.00 \pm 0.00$	-0.01 ± 0.01	-0.04 ± 0.02			
Vertical	[m⋅s <sup>-1</sup> ]	1.98 ± 0.18	1.96 ± 0.21	2.01 ± 0.16			
Forward	[m⋅s <sup>-1</sup> ]	1.16 ± 0.13	0.73 ± 0.12	0.51 ± 0.09			
Knee:							
Backward	[m⋅s⁻¹]	-0.17 ± 0.06	-0.21 ± 0.08	-0.20 ± 0.09			
Vertical	[m·s <sup>-1</sup> ]	0.19 ± 0.11	0.18 ± 0.11	0.15 ± 0.11			
Forward	[m⋅s <sup>-1</sup> ]	0.01 ± 0.01	$0.03 \pm 0.02$	$0.04 \pm 0.03$			
Hip:							
Backward	[m⋅s⁻¹]	-0.03 ± 0.01	-0.05 ± 0.01	-0.05 ± 0.02			
Vertical	[m⋅s⁻¹]	0.01 ± 0.03	0.03 ± 0.03	$0.03 \pm 0.02$			
Forward	[m⋅s⁻¹]	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.01			



Figure 5.4. Stance average induced a) resultant, b) horizontal and c) vertical CM accelerations due to the total joint moments (Total\_JM) and the individual joint moments of the MTP, ankle, knee and hip. Step three is represented by the black bars, step nine is presented by the blue bars and step 19 is represented by the red bars. The tables below the respective figures show the descriptive results of the results of the MBI analysis of the differences between the three steps. For each comparison, there is a qualitative description of the probability of the standardised differences being larger than 0.02, followed by the size (standardised effect) and direction of the differences.

#### 5.3.4 Induced accelerations at the peak force events

At the peak braking force event (Figure 5.5a), differences in ankle moments were most likely large between steps three and nine and very likely moderate between steps nine and 19. Also at the peak braking force event, differences in knee moments were very likely moderate between steps three and nine (Figure 5.5a) while difference in the hip moment (Figure 5.5a) were most likely large (increase) between steps three and nine and likely moderate (decrease) between steps nine and 19. At the peak vertical force event (Figure 5.5b), differences in the ankle moments were likely small between steps three and nine and very likely moderate between steps nine and 19. At the peak vertical force event (Figure 5.5b), differences in the ankle moments were likely small between steps three and nine and very likely moderate between steps nine and 19. At the peak vertical force event (Figure 5.5b), differences in the knee moment between steps three and nine were likely small. At the peak propulsive force event, differences in ankle moments were possibly trivial between step three and nine and possibly small between steps nine and 19, while differences between knee extensor moments were possibly small between steps three and 19.



**Figure 5.5.** Joint moment and induced acceleration data at the instantaneous peak braking (a & d), peak propulsive (b & e) and peak vertical (c & f) force event for steps three (black), nine (blue) and 19 (red). Figures a to c show the joint moments at the events. Figures d and f show the horizontal induced accelerations and figure e shows the vertical induced accelerations.

### 4.3.4.1 Peak braking force event

The horizontal induced accelerations were relatively small (Figure 5.5d) with the ankle plantar flexor moment inducing the largest forward acceleration on the CM at the step three peak braking force event, while the knee flexor moment induced the largest forward acceleration on the CM during steps nine and 19 (Figure 5.6). Apart from the linear acceleration induced by the joint moments (Figure 5.6), angular acceleration were also induced by the joint moments acting on the segments. The FC moment also induced a clockwise angular acceleration on the rear foot and an anti-clockwise angular acceleration on the shank. The FC moment induced an anti-clockwise acceleration on the thigh segment and a clockwise angular accelerations increased the horizontal energy of the LEG and decreased the horizontal energy of the HAT on all three steps. The vertical accelerations induced by the FC moment decreased the vertical energy of the LEG and HAT.

Although the knee moments at the peak braking force events were relatively small, an extensor moment was dominant on step three and flexor dominant on steps nine and 19 (Figure 5.6). The knee flexor moment at the instant of braking during steps nine and 19 induced a clockwise at the rear foot and shank, an anti-clockwise at the thigh and an anti-clockwise acceleration at the HAT. The horizontal induced accelerations increased the horizontal energy of the LEG and decreased the horizontal energy of the HAT on all three steps. The vertical accelerations induced by the FC moment decreased the vertical energy of the LEG and HAT.

The hip extensor moment induced an anti-clockwise angular acceleration at the rear foot. The hip extensor moment induced a clockwise acceleration at the shank at the peak braking force event of step three and anti-clockwise angular acceleration during step nine and 19. The hip extensor moment also induced clockwise angular accelerations at the thigh and an anti-clockwise acceleration at the HAT during all three steps. At all three steps, the hip extensor moment decreased the horizontal and increased the vertical energy of the LEG, and also increased the horizontal and decreased the vertical energy of the HAT. Also, see Chapter 6Appendix A7 for a more complete report of the results.



 $\rightarrow$  Induced accelerations due to knee joint moment

 $\rightarrow$  Total induced Segment accelerations (sum of all joint moment contributions)

 $\rightarrow$  Induced accelerations due to hip joint moment

Figure 5.6. Fore foot, rear foot, shank, thigh and HAT positions and orientation at the instants of peak braking force. The arrows indicate the contribution of the FC (MTP and ankle (purple)), knee (blue), hip (red) and total (black) joint moments on segment accelerations during steps three, nine and 19. The induced CM acceleration is represented by the grey arrow. Below the figures, the joint moments, induced CM accelerations and segment orientations corresponding to the peak braking force event are shown. The segments, coloured arrows and ground reaction force vectors are to scale. The results of the induced power (IP) analysis shows whether a joint moments increased (+) or decreased (-) the energy of either the LEG or HAT. The segments, coloured arrows and grand reaction force vectors are to scale.

#### 4.3.4.2 Peak vertical force event

The vertical induced CM accelerations at the peak vertical force event were dominated by the ankle joint moment (Figure 5.5e). The linear induced acceleration induced by the joint moments are presented in Figure 5.7. The FC moments clockwise angular acceleration at the rear foot and shank while inducing an anti-clockwise angular acceleration at the thigh during all three steps. From step three to nine to 19 the FC moments induced a clockwise angular acceleration at the HAT segment which increased from steps three to nine to 19 due to the increase in the magnitude of the FC moments. On all three steps the FC moments increased the LEG and decreased the HAT horizontal energy, and decreased the vertical energy of both the LEG and HAT.

The knee extensor moment induced the second largest upward acceleration on the CM (Figure 5.5e) during steps three, nine and 19. The knee moment induced an anti-clockwise angular acceleration on the rear foot and shank segments and a clockwise angular acceleration at the thigh segment. An anti-clockwise angular acceleration was induced on the HAT segment during all three steps. The accelerations induced by the knee extensor moment increased the horizontal and decreased the vertical energy of the HAT on all three steps. The horizontal energy at the LEG was decreased on all three steps while vertical energy at the LEG was increased at step three and decreased on step nine and 19.

The hip extensor moments induced an anti-clockwise angular acceleration at the rear foot and shank and a clockwise angular acceleration at the thigh segment on all three steps. An anti-clockwise angular acceleration was induced on the HAT segment on all three steps. The hip extensor moment decreased the horizontal and increased the vertical energy at the LEG, and also increased the horizontal and decreased the vertical energy at the HAT. Also, see Chapter 6Appendix A7 for a more complete report of the results.



 $\rightarrow$  Induced accelerations due to knee joint moment

 $\rightarrow$  Induced accelerations due to hip joint moment

 $\rightarrow$  Total induced CM acceleration (sum of all joint moment contributions)

Figure 5.7. Fore foot, rear foot, shank, thigh and HAT positions and orienation at the instants of peak braking force. The arrows indicate the contribution of the FC (MTP and ankle (purple)), knee (blue), hip (red) and total (black) joint moments on segment accelerations during steps three, nine and 19. The induced CM acceleration is represented by the grey arrow. Below the figures, the joint moments, induced CM accelerations and segment orientations corresponding to the peak vertical force event are shown. The segments, coloured arrows and ground reaction force vectors are to scale. The results of the induced power (IP) analysis shows whether a joint moments increased (+) or decreased (-) the energy of either the LEG or HAT. The segments, coloured arrows and grand reaction force vectors are to scale.

### 4.3.4.3 Peak propulsive force event

The horizontal induced accelerations (Figure 5.5f) at the peak propulsive force event were dominated by the ankle plantar flexor moment. The linear accelerations induced by the joint moments are presented in Figure 5.8. The FC moment induced a clockwise angular acceleration at the rear foot and shank and an anti-clockwise angular acceleration at the thigh segment during all three steps. Upward and forward linear and clockwise angular accelerations induced by the FC plantar flexor moments increased the vertical and horizontal energy of all segments (Figure 5.8).

The knee extensor moment induced an anti-clockwise angular acceleration at the rear foot, an anti-clockwise angular acceleration on the shank and a clockwise angular acceleration at the thigh segment during all steps. The knee extensor moments induced an anti-clockwise angular acceleration at the HAT segment. The induced accelerations from the knee moment decreased the horizontal and vertical energy at the LEG during all three steps. The horizontal and vertical energy of the HAT was increased by the knee extensor moment on all three steps.

Although relatively small, the group mean hip moment was extensor dominant on step three and nine and flexor dominant on step 19. The hip extensor moment induced an anti-clockwise acceleration at the rear foot and shank, a clockwise acceleration on the thigh and an anti-clockwise acceleration at the HAT. At the peak propulsive force event of steps 19, the hip flexor moment induced a clockwise angular acceleration at the rear foot, a clockwise angular acceleration at the shank, an anti-clockwise angular acceleration at the HAT. Also, see Chapter 6Appendix A7 for a more complete report of the results.



 $\rightarrow$  Induced accelerations due to knee joint moment

→ Induced accelerations due to hip joint moment

 $\rightarrow$  Total induced CM acceleration (sum of all joint moment contributions)

Figure 5.8. Fore foot, rear foot, shank, thigh and HAT positions and orientation at the instants of peak braking force. The arrows indicate the contribution of the FC (MTP and ankle (purple)), knee (blue), hip (red) and total (black) joint moments on segment accelerations during steps three, nine and 19. The induced CM acceleration is represented by the grey arrow. Below the figures, the joint moments, induced CM accelerations and segment orientations corresponding to the peak propulsive force event are shown. The segments, coloured arrows and ground reaction force vectors are to scale. The results of the induced power (IP) analysis shows whether a joint moments increased (+) or decreased (-) the energy of either the LEG or HAT. The segments, coloured arrows and grand reaction force vectors are to scale.

## 5.4 Discussion

The changes in external forces that were identified in Chapter 4 were characterised by increased peak braking forces and peak vertical forces from step three to step nine to step 19. However, it is difficult to intuitively predict the contributors to the GRF acting on the CM of the sprinters. The aim of this study was to investigate the effects different forces (joint moments and non-biological) acting on a sprinter have on the sagittal plane acceleration of the sprinter during steps from different phases of a sprint. This aim was achieved by performing an IAA and IPA (Zajac, 2002) to quantify the horizontal and vertical CM accelerations induced on the sprinter using the empirical data from Chapter 4. The knowledge gained from this study can ultimately build on the knowledge gained from Themes 1 and 2 and develop a greater depth of knowledge regarding the underlying mechanisms by which sprinters accelerate their CM during steps during different phases of a sprint.

#### 5.4.1 Induced centre of mass acceleration

The model used for the IAA demonstrated a close match to the measured external ground reaction forces. Absolute RMSD ranged between  $11 \pm 2$  N and  $34 \pm 11$  N. whilst relative errors were 1 - 3% of the peak force excursion which aligns well with previous studies that have shown errors less than 5% when using IAA to investigate running (Dorn et al., 2012). Comparing the total induced ground reaction force time-history to the measured GRF (Figure 5.2) shows that differences were largest at the start and end of ground contact during step 19. This can be attributed to the difficulties in modelling the rapid transition from flight to contact phases at higher running velocities (Hamner et al., 2011). This could be influenced by the relatively large fluctuations in COP at touchdown (Koike et al., 2017). While the comparison between total induced acceleration and measured accelerations shows a good match across the stance phases of all steps, a rigid foot-floor interface at the COP was assumed at the beginning and end of ground contact. A more robust modelling of the foot-floor interaction that includes the deformation of the soft tissues of the foot and the surface at impact, as well as a more precise approximation of the ground contact points (Koike et al., 2017) may provide greater accuracy at the start and end of the stance phases. Nevertheless, the relative errors in the current study shows good accuracy and provides confidence in the interpretation of the results. Of the different inputs that made up the total induced GRF, the largest accelerations induced on the CM were due to the action of the joint moments and accelerations at the foot-floor contact. These results will be discussed in sections 5.4.1.1 and 5.4.1.2 below.

Gravity induced a mean downward acceleration on the body of -9.63 to -9.64 m·s<sup>-2</sup> in all three steps. Although there were considerable changes in segment orientation between steps three, nine and 19, the accelerations transmitted to the ground by the skeletal alignment remained relatively small (0.17 - 0.18 m s<sup>-2</sup>). These were considerably lower than the contribution to vertical acceleration induced by alignment of the segments during walking ( $\sim 3 - 4 \text{ m} \cdot \text{s}^{-2}$ ; Anderson & Pandy, 2002; Liu, Anderson, Schwartz & Delp, 2008). It is important to note that these induced accelerations due to gravity are a function of the foot-floor interaction and segmental alignment (Anderson & Pandy, 2002). The largest differences were probably caused by the different foot-floor interactions during walking and sprinting. The relatively large vertical accelerations due to skeletal alignment during walking tended to occur during mid-stance when the foot was flat on the ground (Anderson & Pandy, 2002), while at the start and end of stance when foot was not flat on the ground, the vertical induced centre of mass accelerations were around 80% smaller (Anderson & Pandy, 2002). Furthermore, the increased knee extension during walking can partly explain the larger contributions by skeletal alignment identified by Liu et al. (2008). Increased leg extension (i.e. more extended knee joint) would resist gravity by allowing compressive forces to be transferred to the ground more effectively (Anderson & Pandy, 2002). Knee extension angles associated with walking (e.g. ~ >157°; Liu et al., 2008) are generally larger compared to maximal sprinting (Chapter 4: Figure 4.14a) where knee angles ranged between 110° to 171° (step 3), 134° to 163° (step 9) and 147° to 162° (step 19) from touchdown to toe-off.

The results of the current theme suggest that as segment angles (i.e. trunk, thigh, and shank) and the knee extension angles during stance increased between steps three, nine and 19, their ability to resist the downward force of gravity would also increase. However, because of the predominantly fore foot contact during sprinting, the increasing segment inclination and knee and hip angles between steps three, nine and 19 could not be translated into an increased vertical centre of mass acceleration contributed by the skeletal alignment. This suggests that there is a

large requirement on the ankle plantar flexors to resist the downward force of gravity during sprinting.

When using the centripetal accelerations of the joints (which are based on segmental angular velocities) of the stance leg as the input to the IAA model, forward accelerations were induced on the centre of mass at the beginning and end of the stance phases (Figure 5.2). The centripetal accelerations appear to have a lesser influence on performance during the stance phases of sprinting when compared to the swing phase (Koike & Sudo, 2015). Nonetheless, the forward accelerations induced by the centripetal accelerations at the joints of the stance leg, which depend on the angular velocities of the HAT, thigh, shank and foot, increased between steps three, nine and 19 with the larger angular velocities of the segments at step 19 contributing 57% of the total horizontal impulse during step 19. Increasing contributions by velocity dependent forces across a range of velocities has also been reported by Hamner and Delp (2013). Furthermore, Hunter et al. (2005) previously identified that a greater mean hip extension velocity was associated with larger propulsive forces while Ae et al. (1992) reported that elite sprinters show an increased during stance. These results show that the increasingly larger clockwise segmental angular velocities identified in Theme 2 (Chapter 4; Figure 4.18) provide an important contribution to the forward acceleration of the CM at high running velocities.

This aligns with coaching theory (e.g. Seagrave, Mouchbahani & O'Donnell, 2009) relating to maximal velocity sprinting mechanics. The coaching theory suggests that during the terminal swing phase, sprinters should aim to generate a large hip extension angular velocity. The idea is that this will effectively reduce horizontal foot velocity and touchdown distances and therefore the braking forces that sprinters generate. Regarding the influence of foot velocity on inducing ground reaction forces, the results of the current study provide quantitative evidence showing the influence of horizontal foot velocity on braking forces (see next section: 5.4.1. Induced accelerations due to accelerations at the foot-floor interface). The results of this study provide further evidence showing the importance of maximising the angular velocity of the segments and the resulting contribution to the forward acceleration of the centre of mass during maximal velocity sprinting. Since the

centripetal velocity of the segments represent the cumulative effect (Hirashima et al., 2008) of all previous forces acting on the system, these results highlight the importance of generating sufficiently large segmental angular velocities during terminal swing through to toe-off.

#### 5.4.1. Induced accelerations due to accelerations at the foot-floor interface

The accelerations at the foot-floor interface induced a backward and upward acceleration on the CM during the braking phase of ground contact. These accelerations, which are induced on the CM as the foot is decelerated following touchdown may be representative of a passive force that is generated when the foot decelerates rapidly following touchdown. Although the relative contributions to the vertical and horizontal GRFs suggest that the horizontal contributions are more influential on the horizontal GRFs, the absolute vertical contributions were larger than the horizontal contributions. Increases in both vertical (moderate positive differences) and horizontal (large positive differences) contributions increased from steps three to nine to 19 which corresponds to the results from Theme 2 (Chapter 4; Table 4.4) where forward and downward foot velocities prior to touchdown increased from step three to nine to 19. The relative contribution to horizontal impulses during the braking phase of ground contact were 145% (step 3), 68% (step 9) and 47% (step 19) while the relative contributions to vertical impulse were 3% (step 3), 5% (step 9) and 6% (step 19). These results provide within-athlete empirical evidence to reinforce the relationship between foot velocity and braking forces (Hunter et al., 2005) and supports the proposal by previous authors that sprinters should minimise the forward velocity of the foot prior to touchdown if they wish to reduce braking forces during stance (Mann & Sprague, 1980; Hunter et al., 2005). However, there may be a point of diminishing returns where continued effort to decrease the horizontal foot velocities prior to touchdown will not result in further decreases in braking impulses and therefore will not be beneficial to performance. A similar limit to performance enhancement was previously shown by Bezodis et al. (2015) who investigated the influence of reducing touchdown distances on sprinting performance. Performing a simulation of the first step in sprinting, Bezodis et al. (2015) reported that decreasing TD distances initially resulted in a performance increase. However, the authors identified a limit to performance enhancement and noted that any further decreases in touchdown distances resulted in a decrease in performance. Therefore, it could be speculated that while sprinters may initially benefit from reducing horizontal foot velocities, excessively small or negative horizontal foot velocities may have no further benefit or be worth the effort needed to achieve those low horizontal foot velocities.

The accelerations at the contact point are calculated from the linear acceleration, angular accelerations and centripetal accelerations of the segment in contact with the ground (Equation 5.5). Across the three steps, there was no clear trend between participants regarding whether ground contact occurred at the fore or rear foot. However, the linear deceleration of the foot at touchdown contributed 125%, 101% and 101% to overall impulse generated by the foot-floor accelerations during the braking phases of steps three, nine and 19 respectively. By experimentally altering the horizontal and vertical deceleration component and increasing the vertical deceleration components of equation 5.5, the influence of this on the braking and vertical impulse could be investigated further. Theoretically, the vertical and horizontal velocity of the foot prior to touchdown can be altered independently through a sensitivity analysis. However, it is unclear to what extent this is practical as it is unlikely that sprinters can influence one variable without changing another. Furthermore, it is unclear what effect these changes in either horizontal or vertical foot velocities have on other components of ground contact (e.g. total vertical impulse and propulsive impulse) which may negatively influence performance. Researchers and coaches are encouraged to explore the influence of altering foot velocities prior to touchdown to identify possible influences on their performance.

### 5.4.3 Joint moment induced accelerations

Joint moments were the dominant source of CM acceleration during the stance phases of steps three, nine and 19. This is different from activities like overarm throwing (Hirashima et al., 2008) and the swing phase in sprinting (Koike & Sudo, 2015) where the motion dependent term (e.g. centripetal accelerations) was the dominant contributor to induced accelerations. This may be related to the nature of the task where during the swing phase or overarm throwing the aim is to maximise the end-point velocity, while during ground contact in sprinting the aim is to maximise the velocity of the CM, which is much heavier and proximal to the joints where the moments are generated. The accelerations induced by the joint moments increased vertically and decreased horizontally from steps three to nine to 19 (Figure 5.3). This was influenced by the increasingly more vertically oriented segments (i.e. more upright posture) during ground contact (Figure 5.6, Figure 5.7 & Figure 5.8), which caused in an increasingly more inclined induced acceleration vector. Rabita et al., (2015) suggested the possible importance of the hip and ankle moments in orientating the resultant GRF vector. However, the results of the current investigation suggest that the orientation of the segment of the sprinter is important when orientating the GRFs more horizontally.

The increased touchdown distance and decreased toe-off distances associated with steps nine and 19 resulted in increasing braking and decreasing propulsive forces, respectively. Although lower touchdown distances have previously been associated with a lower braking impulse (Hunter et al., 2005), the results of the current study provide some important insight showing how touchdown and toe-off distances may influence braking and propulsive forces generated by sprinters. Chapter 3 showed that changes in touchdown and toe-off distances were due to shank and trunk becoming more inclined as the sprint progressed. The current results suggest that the decreasing anterior accelerations induced on centre of mass between steps three, nine and 19 (Figure 5.4) were probably dictated by the increasingly more inclined acceleration vectors induced on the HAT segment at the peak braking force (Figure 5.6) and peak propulsive events (Figure 5.8). Since the type of joint moments (i.e. flexor or extensor) did not necessarily change between the steps, the differences in the anterior-posterior accelerations induced on the centre of mass would have been influenced by the differences in segmental orientation between steps three, nine and 19. This is especially clear when comparing the differences in the anterior-posterior accelerations induced by the ankle plantar flexor moment during the braking phases of steps three, nine and 19 (Figure 5.2, Figure 5.6). These results highlight the influence the sprinters' posture at touchdown and throughout stance has on their performance. When combined with the results of the foot-floor acceleration as discussed earlier, this further highlights the importance of the sprinter's 'front side mechanics' (Mann, 2007, p. 86) and its influence on the braking forces generated during stance. Coaches and sprinters are therefore encouraged to develop the mechanics during the terminal swing and braking phases at varying running velocities and across a range of body orientations with the aim of decreasing touchdown distances. However, there may exist an optimum (Bezodis et al., 2015) and it is unclear how changes to touchdown distance will affect other variables important to performance including vertical force production (e.g. Weyand et al., 2000) and postural stability (e.g. Kugler & Janshen, 2010). Since larger vertical forces are important to achieving high running velocities (Weyand et al., 2000), finding the optimal touchdown distance may be a trade-off between generating braking forces and maximising vertical force production. The mechanism by which sprinters can minimise braking forces while ensuring performance is enhanced requires further exploration.

## 5.4.3.1 Foot complex (FC)

The MTP joint has generally been described as a large absorber of energy (Stefanyshyn & Nigg, 1997; Smith et al., 2014; Bezodis et al., 2014; Chapter 4: Figure 4.11). When acting in isolation, the MTP moment induces a backward acceleration on the CM (Figure 5.3 a-f) which decreases the horizontal energy of the CM. These results associated with the two-point contact model agreed with Koike, Ishikawa and Ae (2010) who used a similar foot contact model to the one in this study. The differences in induced accelerations by the MTP joint between steps three, nine and 19 were generally small and not meaningful. It has been suggested that a larger MTP moment may allow athletes to increase their forward lean and as such achieve a more horizontally orientated take-off trajectory (Goldmann, Sanno, Willwacher, Heinrich & Brüggemann, 2013). This would place the sprinter into a more appropriate posture for the more powerful plantar flexors of the ankle to propel the sprinter forwards. Although the results suggest that an MTP plantar flexor moment has a detrimental effect on the forward progression of the CM (i.e. by inducing small backward CM accelerations), increasing the moment about the MTP joint, however, has an important performance enhancing function by generating an upward acceleration on the CM towards the end of stance (Figure 5.3 b, d, f).

The ankle plantar flexor moment induced the largest horizontal and vertical accelerations on the CM. These results are in line with previous studies investigating the induced CM accelerations during a single sprinting ground contact (Cabral et

al., 2013) or phase (Debaere et al., 2015; Koike & Nagai, 2015) and sub-maximal running (Dorn et al., 2010; Hamner & Delp, 2013). The increasingly larger ankle plantar flexor moment resulted in increased vertical and decreased horizontal induced CM accelerations (Figure 5.4). This may be linked to the more inclined shank, trunk and rear foot segments leading to larger vertical accelerations being induced on the CM. Although there were no clear differences in vertical impulse generated by the ankle plantar flexor moment between steps three, nine and 19, the increasing vertical CM accelerations induced by the ankle plantar flexor moment reflects the increased requirement to generate large vertical forces at higher running velocities (Weyand et al., 2000).

Between steps three, nine and 19 the combined foot complex (FC) plantar flexor moments induced increasingly larger forward and upward accelerations on the rear foot and shank. This opposed the increasingly larger downward and backward accelerations induced on the shank and rear foot segments by the more proximal joint moments (Figure 5.6, Figure 5.7 & Figure 5.8) and gravity, particularly during steps nine and 19. As this occurred at the time when the ankle joint was either dorsiflexing (at the peak braking force event) or fixed (around the peak vertical force event), the FC plantar flexor moments played an important role in providing a stable ankle joint so that accelerations induced by more proximal joint moments are transferred to the ground. A previous study has shown that during sprinting, the ankle plantar flexors operate at a larger relative effort when compared to the knee extensors (96% vs. 76%; Kulmala et al., 2016). This is may be due to the increasing need to resist the dorsiflexion that would result from the accelerations induced at the shank and rear foot by the proximal hip and knee extensor moments. Indeed, a stiffer ankle (i.e. more resistant to dorsiflexion) may be linked to increased performance during the first stance phase in sprinting (Charalambous et al., 2012; Bezodis et al., 2015) and maximal velocity (Nagahara & Zushi, 2016) while a stiff foot-floor joint (i.e. a fixed angle between the foot and the ground) has been experimentally shown to transfer larger accelerations generated by the hip extensor moment to the ground (Cabral et al., 2013). The ability of the FC to transfer acceleration from proximal segments to the ground during the peak braking (Figure 5.6) and peak vertical (Figure 5.7) force events is important in all three steps analysed and may represent a key factor limiting maximal sprinting performance.

This may relate to the ability of the ankle to remain stiff, and so limit dorsiflexion following touchdown. In practical situations, this could be assessed during sprinting tasks by measuring the dorsiflexion range of motion following touchdown, where a smaller or decreasing dorsiflexion range of motion possibly represents a stiffer ankle. Furthermore, reactive exercises including depth jumps or continuous rebound ankle hops, which have previously been associated with performance during the maximal velocity phases of sprinting (e.g. Bret, Rahmani, Dufour, Messonnier & Lacour, 2002; Bissas & Havenetidis, 2008; Nagahara, Naito, Miyashiro, Morin & Zushi, 2014) could be used to monitor changes in ankle joint stiffness. However, touchdown position of the foot and shank needs to be taken into consideration as this may determine the dorsiflexion range of motion following touchdown. For example, a more plantar flexed ankle at touchdown may undergo larger dorsiflexion following touchdown. The practical implications of this will be discussed in section 5.4.4.

During the propulsive phase, large horizontal and vertical accelerations are induced by the ankle moment on the CM. This is similar to previous research showing that the soleus and gastrocnemius are the largest contributors to forward acceleration of the CM during the propulsive phase of sub-maximal running (Hamner et al., 2010) with the soleus being the main contributor across a range of sub-maximal running velocities (Hamner & Delp, 2013). At the peak propulsive force event the FC plantar flexor moment (of which the ankle moment plays a large part) induced upward and forward accelerations at the stance leg segments and HAT. This is unlike the peak braking and peak vertical force events where the FC induced a forward and upward accelerations at the stance leg segments but a backward and upward accelerations at the HAT. A substantial period of power generation has previously been shown to occur at the ankle joint prior to toe-off during all phases in sprinting (e.g. Johnson & Buckley, 2001; Bezodis et al., 2008; Charalambous et al., 2011; Bezodis et al., 2014; Chapter 4: Figure 4.12d). The power generating capability of the ankle plantar flexors, which is likely aided by the release of elastic energy stored during the earlier phases of stance (Cavagna et al., 1971; Hunter et al., 2005), has previously been related to sprint performance at higher running velocities (Nagahara, Matsubayashi et al., 2014). A powerful plantar flexion of the ankle and MTP joint during the propulsive phase of ground contact therefore appears to be an important mechanism to propel the sprinter forward and upward into the next flight phase. The practical implications of this will also be discussed in section 5.4.2.

## 5.4.3.2 Knee

The knee moment was characterised by a flexor moment directly after touchdown, an extensor moment during mid-stance and a flexor moment before toe-off (see Chapter 4; Figure 4.14c). Although the knee flexor moment at the peak braking force event of steps nine and 19 decelerated the HAT (i.e. decreased the energy of the HAT) the increasingly larger forward acceleration of the LEG meant that the knee flexor moment contributed an increasingly larger forward impulse on the CM between steps three  $(0.00 \pm 0.01 \text{ m} \cdot \text{s}^{-1})$ , nine  $(0.02 \pm 0.02 \text{ m} \cdot \text{s}^{-1})$  and 19  $(0.03 \pm 0.02 \text{ m} \cdot \text{s}^{-1})$  (Table 5.3). Although, a knee flexor moment was dominant immediately following touchdown on all three steps (Figure 4.14c) it could be speculated that the more inclined shank associated with steps nine and 19 increased the effectiveness of the knee flexor moment to contribute to forward CM acceleration. This will ensure that the linear acceleration vector at the proximal and distal ends of the shank is more horizontally orientated, increasing the forward and backward acceleration of the knee and ankle joints respectively. This links to the geometric constraints theory (van Ingen Schenau et al., 1987) which suggests that at certain orientations (i.e. close to the vertical), segment rotational motions are better able to contribute to the horizontal translation of the CM.

Previous research has suggested that the knee moment plays an important role in transferring energy from proximal to distal segments (Bezodis et al., 2008). The results of the current study suggest that a knee flexor moment may play an important role in ensuring that the clockwise accelerations induced at the thigh by the hip extensor moments are transferred to the shank. Following touchdown, the knee flexor moment, which generates knee flexion, opposes the backward and anticlockwise acceleration induced on the shank by the hip extensor moment (Figure 5.6). The knee flexor moment therefore provides stability at the shank allowing the clockwise rotating thigh to translate the upper body (HAT) forward and upward via the knee joint (Figure 5.6). One first glance it might therefore seem beneficial to have a large knee flexor moment, which could be achieved through and increased TD distance (Sun et al., 2015). However, increasing TD distances is not

recommended as this could increase braking force by placing the sprinter in a less efficient position to generate horizontal forces. Furthermore, increased TD distances could increase the strain experienced by the hamstrings (via increased hip extensor and knee flexor moments) and therefore increase the risk of injury (Sun et al., 2015). Rather coaches and sprinters should attempt to effectively reduce TD distance therefore possibly negating the need for a large knee flexor moment to accelerate the sprinter over the contact point.

A second function suggested for the knee moment is to support the rise of the CM during the initial acceleration phase (Charalambous et al., 2011; Debaere et al., 2015) and maintain the height of the CM during the transition and maximal velocity phases (Johnson & Buckley, 2001; Bezodis et al., 2008). After about 0.02 s of stance, the knee extensor moments induced a backward and upward acceleration on the CM (Figure 5.3). The knee extensor moment induced the second largest upward acceleration on the CM. This therefore supports the theory that the knee plays an important role in providing upward acceleration on the CM. However, the larger knee extensor moments identified in Theme 2 (Chapter 4; Figure 4.14c) and more upright postures associated with steps nine and 19 did not translate into larger upward CM accelerations (Figure 5.4). Although the knee extensor joint moment induced small forward and upward accelerations on the HAT, this appears to be limited since a backward and downward acceleration was also induced on the rear foot and shank. Unless a sufficiently large FC plantar flexor moment is present to ensure the ankle is suitably stiff to oppose the downward and backward accelerations induced on the rear foot and shank, the effectiveness of the knee extensor moment in accelerating the HAT upward is limited. This is analogous to stepping up onto a hard surface that resists the downward forces generated by the leg or stepping up onto a soft surface that deforms under the forces applied. A knee extensor moment is therefore reliant on a stable rear foot and shank segment in order to accelerate the sprinter forward and upwards. If the rear foot and shank are sufficiently supported by the plantar flexor FC moments, a knee extensor moment has the potential to induce a larger upward and forward acceleration at HAT.

### 5.4.3.3 Hip moment

From touchdown until 0.080 to 0.120 s, the hip extensor moment induced a relatively small backward and upward accelerations on the CM compared to the distal joint moments. This was consistent across all three steps and was predominantly influenced by the backward accelerations induced on the segments of the stance leg (Figure 5.6 & Figure 5.7). These results are in agreement with Cabral et al. (2013), Koike and Nagai (2015) and Debaere et al. (2015), but seem counter intuitive given the relatively large hip extensor moments and powers generated at the hip joint compared to the ankle and knee (Cabral et al., 2013; Debaere, Delecluse et al., 2013; Chapter 4; Figure 4.16 c & d). Furthermore, "the hip extension theory" (Hunter et al., 2004c, p. 1445) states that the clockwise rotation of the thigh, caused primarily by the hip extensors, is an important contributor to the propulsive GRF and suggests that a powerful hip extension is important for sprinting success. According to the results of the current study, the hip extensor moment induced a forward acceleration on the HAT (i.e. increase in the horizontal energy of the HAT) and a clockwise acceleration on the thigh and anti-clockwise acceleration of the shank and rear foot segments. These induced angular accelerations resulted in a backward and downward linear acceleration induced on the segments of the stance leg which could not be translated into a forward acceleration at the whole-body centre of mass. Therefore, unless the clockwise angular accelerations induced on the thigh are translated to the shank through the action of the knee flexor moments and then to the ground by the action of the FC plantar flexor moment, the acceleration induced by the hip extensors cannot be translated into large propulsive GRF.

Interestingly, the results also showed that at the peak braking force event of step three (Figure 5.6), the hip extensor joint moment induced a clockwise angular acceleration on the shank while a hip extensor moment induced an anti-clockwise acceleration on the shank during steps nine and 19. This negated the need for a knee flexor moment at peak braking force events of step three to transfer the accelerations from the thigh to the shank. Although it is not possible to identify which muscles played a role in generating the different joint moments, a recent experimental study has shown that hamstring activation and eccentric peak torque capability play an important role in horizontal force production (Morin et al., 2015). The bi-articular hamstrings and potentially the gastrocnemius may therefore play an important role in generating both hip extension and knee flexion.

A hip extensor moment may also play an important role in providing support to the upper body by assisting the knee extensors in resisting knee flexion during the stance phases of steps nine and 19. The results show that a hip extensor moment has the potential to generate knee extension (Figure 5.7) by inducing clockwise and anti-clockwise angular accelerations at the thigh and shank respectively. This may provide further explanation why knee extension moments and powers can remain relatively small during the stance phases of sprinting (Bezodis et al., 2008) and therefore work at a lower relative effort than the ankle joint (Kulmala et al., 2016). However, the effectiveness of the hip extensor moments in inducing upward CM accelerations is also dependent on a stable rear foot and shank to transfer accelerations to the ground.

### 5.4.4 Practical Implications

The new understanding gained from these results and their interpretation in the context of existing relevant literature can be used to inform future technical or physical preparation aspects of sprinting. Firstly, the results of the current study provide empirical evidence showing the link between horizontal foot velocities prior to touchdown and braking forces. In the current study 145% (-0.01  $\pm$  0.01 m s<sup>-1</sup>), 68% (-0.05  $\pm$  0.01 m s<sup>-1</sup>) and 47% (-0.08  $\pm$  0.01 m s<sup>-1</sup>) of the braking impulse was generated by the accelerations at the foot-floor interface during steps three, nine and 19 respectively. This study provided direct evidence to support the hypothesis put forward by various authors (Mann & Sprague, 1983; Hay, 1994) that sprinters should aim to reduce braking forces by minimising the forward velocity of the foot prior to touchdown. Furthermore, the results of this study showed that 125% (step 3), 101% (step 9) and 101% (step 19) of the braking impulse generated by the foot-floor acceleration was due to the foot being decelerated at touchdown. The increasing contribution of the foot-floor accelerations to braking and vertical impulses between steps three, nine and 19 and could be attributed to the increases in forward and downward velocities of the foot identified in Theme 2 (Chapter 4; Table 4.4). This supports the technical focus, which suggests that sprinters should aim to develop a larger backward angular acceleration of the thigh (Seagrave et al.,

2009). This technical focus will not only reduce the forward velocity of the foot immediately prior to touchdown, but also contribute to large centripetal accelerations (via larger clockwise rotations (sprinting left to right) of the thigh and shank) at the segments of the stance leg which contributed an important forward acceleration on the CM at higher running velocities.

Secondly, the results of this study support the importance of posture (i.e. orientations of segments) for performance as previously reported by scientific (e.g. di Prampero et al., 2005; Kugler & Janshen, 2010) and coaching literature (e.g. Seagrave et al., 2009; Crick, 2013e). As the orientations of the shank and HAT became upright, the accelerations induced on the segments by the ankle joint moments became more vertically orientated. These more vertically orientated linear induced acceleration vectors combined with the increasing magnitudes of the ankle plantar flexor moments as the sprint progresses contributed to the increasing vertical GRF (Figure 5.5). This plays an important role during the acceleration phase where a sprinter's segmental orientations show step-to-step changes (Chapter 3; Figure 3.10). Cueing a more efficient posture would provide the coach with a powerful tool to influence the vertical and horizontal forces athletes can generate. For example, coaches could emphasis a forward orientated trunk during the initial acceleration phase to ensure increased horizontal forces are generated. Also, specialised equipment (e.g. heavy sleds) could be used to place sprinters into more appropriate positions to emphasise horizontal force production (Morin, Petrakos, Jimenez-Reyes, Brown, Samozino & Cross, 2016). Furthermore, an interesting finding of Theme 3 was that different magnitudes of acceleration were induced by the joint moments at the different segments. Larger accelerations were induced on lighter segments (e.g. shank, foot), however, lighter segments play a relatively small role in influencing the overall acceleration and position of the CM compared to a relatively massive segment like the thigh and trunk. From this, it could be speculated that ensuring a more appropriate orientation of more massive segments (e.g. trunk) could be more influential to performance than cueing the position of lighter segments like the shank and foot. Future studies are encouraged to identify to what degree individual segment kinematics can be altered and how these changes influence the force generating capability of athletes.

Finally, the results of the current study also emphasised the importance of the ankle plantar flexor moment. Firstly, a plantar flexor moment resists ankle dorsiflexion and stabilises the position of the foot relative to the ground (Figure 5.6) and secondly it induces large forward accelerations on the CM through a powerful plantar flexion of the ankle joint during the propulsive phase of ground contact (Figure 5.8). While pre-activation of the muscles surrounding the ankle joint (e.g. via ankle dorsiflexion) can help sprinters generate a stiffer ankle (Mero & Komi, 1987, Seagrave et al., 2009), sprinters should also develop the neuromuscular ability to quickly generate large ankle plantar flexor moments. The ankle plantar flexors' ability to both maintain a stiff ankle and generate energy via plantar flexion can be develop through isolated ankle plyometric and dynamic multi-joint exercises. Specific plyometric exercises that isolate the ankle (e.g. ankle hops) and therefore condition the plantar flexors to quickly generate force (Kubo, Morimoto, Komuro, Yata, Tsunoda & Kanehisa, 2007), thereby providing a stiff ankle after touchdown and enhancing the power generating capacity of the plantar flexors during the propulsive phase, could be included in an athletes training. Furthermore, the use of dynamic multi-joint conditioning exercises like heavy sled sprinting (Petrakos, Morin & Egan, 2015; Morin et al., 2016) which promotes force production via the fore foot is encouraged. Although the exact mechanism of how heavy sled sprinting elicits improvements in sprinting performance is still unclear, heavy sled sprinting has previously been shown to increase the horizontal force production capability and improve 5 m and 10 m performance during sprinting (Morin et al., 2016).

The ankle plantar flexor moment during its negative power phase is largely generated by the instantaneous hip and knee extensor moments (Koike & Nagai, 2015). This is because at any one instant, the hip and knee extensor moments contribute to the vertical and horizontal force at the ankle joint, while also contributing to the cumulative motion of the segments; which also contribute additional forces at the ankle joint. Heavy sled sprinting not only has the potential to overload the hip and knee extensors while the athlete is in a more specific position, but also dynamically overload the ankle plantar flexors by generating large downward and backward orientated forces at the ankle joint. This will develop the ankle plantar flexors' ability to generate a stiff ankle joint to transmit the accelerations generated by the hip and knee extensors more effectively.

## 5.5 Conclusions

The first research questions posed in the introduction of this chapter asked what the primary contributors to CM acceleration are and how these contributions change between the initial acceleration, transition and maximal velocity phases. The study performed in this chapter identified the contributors to CM acceleration using an IAA. The largest contributors to CM acceleration were the joint moments and the accelerations at the foot-floor contact point. The backward and upward induced acceleration resulting from the accelerations at the contact point increased from steps three to nine to 19. This coincided with an increasing forward and downward velocity of the foot prior to touchdown, which was reported in Theme 2 (Chapter 4; Table 4.4). Out of the four joint moments investigated in this study, the plantar flexor moment at the ankle induced the largest forward and upward acceleration on the CM. The decreasing forward and increasing upward induced accelerations between steps three, nine and 19 were associated with the increasingly more vertical orientation of the segments. The joint moments of the knee and hip induced relatively small accelerations on the CM. This suggests that their role is more related to generating large acceleration at the thigh, and appropriately transferring accelerations (e.g. knee flexor moment) from the thigh to the shank.

Because joint moments and segmental orientations play a large role in determining the CM accelerations, the research question - *'Why do the segmental accelerations induced by the different joint moments change between the initial acceleration, transition and maximal velocity phases?'* - was posed in the chapter. To address this research question, three peak force events present in all three steps were selected to analyse how different joint moments induced accelerations on the different segments within the IAA model. These included the events when peak braking, peak vertical and peak propulsive forces occurred. This analysis revealed that at the peak braking force event the FC plantar flexor moment and to a lesser extent the knee flexor moment on steps nine and 19 opposed the backward and downward acceleration induced by the knee and hip extensor moments. This ensured a fixed knee joint to allow the thigh and HAT to translate forward and upward via a fixed knee joint. At the peak vertical force event, both the hip extensor and knee extensor moments contributed to the upward acceleration on the CM. However, these were dependent on the ability of the FC plantar flexor moments to

induce large forward and upward accelerations to stabilise the shank and rear foot segments against the accelerations induced by the more proximal segments and therefore ensure accelerations induced by proximal moments are transferred to the ground. At the peak propulsive force events, the plantar flexors of the ankle increased the horizontal and vertical energy of the whole body, emphasising the importance of a powerful plantar flexion during the propulsive phase of ground contact. This suggests that the work done by the plantar flexors is important to not just transfer accelerations to the ground but also to accelerate the whole body forward and upward through a powerful plantar flexion of the ankle.

### 5.6 Chapter Summary

The aim of Theme 3 (Induced acceleration analysis) was to investigate the effects different forces (joint moments and non-biological) acting on a sprinter have on the sagittal plane acceleration of the sprinter during steps from different phases of a sprint. The results of the current study were able to build on the knowledge gained from Themes 1 (Chapter 3) and Theme 2 (Chapter 4) and develop a greater depth of knowledge regarding the underlying mechanisms by which sprinters accelerate their CM during steps during different phases of a sprint. Evaluation of the model revealed that it realistically replicated the external kinetics of steps three, nine and 19. By running the IAA using individual inputs generated from the empirical data gathered for Theme 2 (Chapter 4), individual contributions to CM and segment accelerations were identified. A major contributor to the backward and upward acceleration of the CM during the braking phase of ground contact were the accelerations at the foot-floor interface which resulted from the deceleration of the foot at touchdown. Coaches should therefore strive to encourage sprinters to minimise the forward and maximise the downward velocity of the foot prior to touchdown. Especially as a sprint progresses, this will help to minimise braking and increase vertical GRF over the first 0.03 s of stance.

While the initial analysis revealed that the joint moments induced the largest forward and upward accelerations on the CM, a more in-depth analysis showed that the ankle plantar flexor moments had the largest relative contribution to the upward and forward progression on the CM. The current study showed that the ankle moment contribution decreased horizontally and increased vertically from steps three to nine to 19. This was due to the orientation of the sprinter becoming more inclined between steps three, nine and 19. To further investigate the effect the different joint moments had on the different segments of the model (i.e. rear foot, shank, thigh and HAT), three force events present in all three steps were identified and investigated in more detail. This analysis revealed that the knee flexor and ankle plantar flexor moments induced forward orientated accelerations on the segments of the stance leg which increase the horizontal energy of the stance leg. The hip and knee extensor moments induced backward accelerations at the segments of the stance leg and forward accelerations at the upper body. This decreased the horizontal energy of the stance leg and transferred it to the upper body. During the peak vertical force event, both the hip and knee extensors were able to induce upward accelerations on the CM. The magnitude of these accelerations are limited by the ability of the ankle and MTP plantar flexor to maintain a stable rear foot segment and resist the downward accelerations induced on the rear foot by the hip and knee moments. Towards toe-off, the FC plantar flexor moment accelerated the segments of the stance leg and upper body forward and upward. These results suggest an important dual role of the plantar flexors of the ankle and MTP where they transfer accelerations to the ground during the first half of stance and accelerate the whole-body forwards and upwards via a powerful plantar flexion prior to toe-off.

## Chapter 6 - General Discussion

## **6.1 Introduction**

There is currently limited research on the kinematic and kinetic changes that occur as a sprint progresses. The aim of this thesis was to investigate biomechanical differences in technique between the initial acceleration, transition and maximal velocity phases of a sprint. The overall purpose of this thesis was to increase the conceptual understanding of the biomechanical changes in technique as a sprint progresses, and help develop coaching knowledge of biomechanical differences between the initial acceleration, transition and maximal velocity phases. Following a review of the current literature (Chapter 2) a thematic approach was used to address the aim of this thesis. The thematic approach was based on three key research themes that emerged from the literature. These included:

- 1) Theme 1: Phase analysis
- 2) Theme 2: Technique analysis
- 3) Theme 3: Induced acceleration analysis

The key findings from the three themes and their corresponding research questions, which were addressed by the investigations outlined in Chapters 3 - 5, are discussed in this chapter. Additionally, the appropriateness of the methods used throughout this thesis, and the novel contributions to knowledge including practical implications, will be discussed. Finally, potential future investigations will be suggested.

# 6.2 Addressing the Research Themes

The three themes and their respective research questions emerged from the review of literature (Chapter 2). A sprinter accelerating from the starting blocks up to maximal velocity undergoes large changes in kinematics and kinetics that influences both the magnitude and direction of force production. To maximise performance as a sprinting progresses, it is important to understand the kinematic and kinetic changes that occur during maximal sprinting. Although some research has previously reported step characteristics and kinematics across various steps in sprinting, there is still a lack of scientific evidence of the kinematic changes
associated with a sprinter's posture. A better understanding of the characteristics of the phases within maximal sprinting was therefore required. This lead to the first theme of this research:

Theme 1: **Phase analysis:** The aim of Theme 1 was to investigate differences in step-to-step changes in step characteristics and kinematic variables between the initial acceleration, transition and maximal velocity phases. Theme 1 increased understanding of the initial acceleration, transition and maximal velocity phases and which can ultimately help to develop the technical model of different phases in sprinting. Specifically, between-step changes of step characteristics and kinematic variables at touchdown and toe-off associated with the initial acceleration, transition and maximal velocity phases were investigated. These phases were previously identified using velocity profiles of multiple athletes (e.g. Delecluse et al., 1995), by identifying breakpoints in the step-to-step progression of different measures (e.g. Nagahara, Matsubayashi et al., 2014) or identifying specific events (e.g. Čoh et al., 2006). However, it is unclear how the phases which were identified using different measures the phases which were identified using different how the phases which were identified using different how the phases which were identified using different how the phases which were identified using different measures (e.g. Čoh et al., 2006). However, it is unclear how the phases which were identified using different measures the phases which were identified using different measures (e.g. These phases which were identified using different measures compared. This formed the basis of the first research question of Theme 1:

# Research question (i) - How comparable are the breakpoints separating the initial acceleration, transition and maximal velocity phases when identified using different measures?

Different measures proposed by research and coaching literature to identify the breakpoint steps ( $T_{start}$ ) which separate the initial acceleration from the transition phase, and the breakpoint steps ( $MV_{start}$ ) which separate the transition phase from the maximal velocity phase were compared. The measures used to identify  $T_{start}$  included: centre of mass height (CM-h; Nagahara, Matsubayashi et al., 2014), touchdown shank angles (Crick, 2013e) and the event when flight times equalled or exceeded contact times ( $CT \le FT$ , Čoh et al., 2006). Measures used to identify  $MV_{start}$  included CM-h (Nagahara, Matsubayashi et al., 2014) and touchdown trunk angles (Crick, 2013e). Sagittal plane kinematic data was collected while participants performed 3 – 5 maximal 50 m sprints on two separate days. In order to compare phase occurrences (i.e. differences in  $T_{start}$ ,  $MV_{start}$ ) identified using the different

measures, an RMSD between the  $T_{start}$  steps (based on CM-h, shank angles and CT $\leq$ FT) as well as between the MV<sub>start</sub> steps (based on CM-h and trunk angles) was therefore calculated.

The results revealed that, while ranges of T<sub>start</sub> and MV<sub>start</sub> steps detected using either CM-h or segment angles at touchdown were comparable, the within-trial RMSD calculated between CM-h and segment angles showed differences up to 2.3 steps. These differences were due to the CM being a more global variable influenced by multiple segments while measuring changes in shank and trunk angles only provide information about what is happening locally at the segments. When comparing the step CT≤FT to the other T<sub>start</sub> steps, it was concluded that CT≤FT was not representative of changes in the postural measures used in the current study. CT≤FT is possibly more influenced by the sprinter's velocity and ability to generate sufficiently large vertical impulses during decreasing ground contact times.

This study also revealed the consistency of the T<sub>start</sub> and MV<sub>start</sub> step ranges identified between two days. This further verifies the location of these breakpoint steps and reinforces the idea proposed previously to sub-divide the acceleration phase in sprinting based on abrupt changes in kinematics (Nagahara, Matsubayashi et al., 2014). It was concluded that although segment angles provide an appropriate measure in more applied settings as a way to provide quantitative feedback to coaches and athletes; the CM-h represents a more holistic measure to quantify total body changes. CM-h was therefore adopted for the remainder of this study to sub-divide the 50 m trials and address the second research question of Theme 1:

# Research question (ii) - How do step-to-step changes of step characteristics and kinematics differ between the initial acceleration phase, transition phase and maximal velocity phase?

The range of  $T_{start}$  and  $MV_{start}$  steps identified from the fastest trials of each participant from each data collection day were used to sub-divide the 50 m trials into the initial acceleration, transition and maximal velocity phase. Step 1 - 3 were identified as occurring in the initial acceleration phase, steps 6 - 13 were identified

as occurring in the transition phase and steps 17 onwards were identified as occurring in the maximal velocity phase (Chapter 3, Figure 3.6). The step characteristics and step-to-step changes in kinematic variables at touchdown and toe-off exhibited clear differences in the step-to-step patterns of change during the initial acceleration, transition and maximal velocity phases of the 50 m sprints. The study also highlighted that the participants adjusted their step characteristics by independently adjusting the components of step length (i.e. contact and flight distance) and step frequency (i.e. contact and flight time).

The initial acceleration phase was characterised by a relatively steep rise in step velocity, step length and step frequency. At the start of the transition phase ( $T_{start}$ ), the participants had reached 65% to 77% of maximal velocity (6.06 m·s<sup>-1</sup> to 7.83 m·s<sup>-1</sup>). These were slightly lower than the 75 to 80% of maximal velocity proposed by the British Athletics model (Crick, 2013g). This may be due to an earlier occurring T<sub>start</sub> (i.e. steps 4 – 6) than is suggested by the British Athletics coaching literature which was based on a qualitative analysis of elite sprint races (i.e. between steps 5-7; Crick, 2013e). Compared to the initial acceleration phase, further step-to-step increases in step velocity during the transition phase were smaller. At the start of the maximal velocity (8.19 m·s<sup>-1</sup> to 10.07 m·s<sup>-1</sup>). The British Athletics performance model for sprinting (Crick, 2013g) suggests that sprinters will have reached 95% of their maximal velocity at the end of the transition phases. Although step-to-step increases in step velocity still occurred these were relatively small in comparison to the previous phases (Chapter 3; Figure 3.7).

Since step velocity is the product of step frequency and step length (Hay, 1994), understanding the changes in these variables will increase understanding of how step velocity is developed. During the initial acceleration phase, large step-to-step increases in step frequency were likely due to larger step-to-step decreases in contact times relative to the increases in flight times (Figure 3.9 a & b). The relatively large step-to-step increases in step frequency have previously been correlated with acceleration over the first three steps of a sprint (Nagahara, Naito, Morin & Zushi, 2014). This represents an important characteristic of the initial acceleration phase. Throughout the transition phase, although contact and flight times continued to

decrease, step frequency plateaued as increases in flight times were approximately matched by decreases in contact times. During the initial acceleration phase, step lengths increased through increases in both contact distances and flight distances (Figure 3.9 c & d). This is different to the transition phase where further step-to-step increases in step lengths were largely due to increases in its flight component (flight length) while changes in contact distance plateaued. This meant that during the initial acceleration phase, the work done by the participants could increase by increasing both GRF and distance (i.e. contact distance) while during the transition phase any further increases in work done during ground contact were dependent on increases in GRF. By the maximal velocity phase, increases in step length were relatively small, which have been shown to continue to increase throughout a 100 m sprint (Ae et al., 1992).

The relatively large step-to-step increases in contact distances during the initial acceleration phase has also previously been reported by Nagahara, Matsubayashi et al. (2014) and will have resulted from larger increases in TD distances compared to the decrease in toe-off distance (Figure 3.9 c & d). This increased the range of motion over which the participants could produce force (Mann, 2007) while contact times decreased from one-step to the next. The increasing TD distances during the initial acceleration phase resulted from increasing touchdown shank (6 to 12° per step) and trunk angles (2 to 9° per step) (Figure 3.10 a & g). These results aligned with British Athletics coaching literature, which suggested that touchdown shank angles should increase between 6 to 8° per step during the initial acceleration phase (Crick, 2013e). The increasing shank angle and resulting touchdown distance may have an important functional role allowing sprinters to generate larger vertical GRFs early during ground contact and facilitating the step-to-step increases in flight times (Crick, 2013e; Chapter 3: Figure 3.8). While step-to-step increases in touchdown shank angles and therefore touchdown distances are an characteristic of the initial acceleration and transition phases, excessive increases in shank angles may be detrimental to generating large propulsive forces as they limit the toe-off distances and therefore absolute magnitudes of propulsive forces sprinters can generate during shorter contact times. Furthermore, ensuring step-to-step increases in shank angles are sufficiently small may be important to ensure touchdown distances, which have previously been associated with braking forces (Hunter et al., 2005),

remain relatively small compared to the transition and maximal velocity phases. This was explored in Theme 2 (Technique analysis) and Theme 3 (Induced acceleration analysis) and will be discussed later.

During the transition phase, step-to-step changes in contact distance plateaued. This will have resulted as TD distances and toe-off distances changed at a similar rate between successive steps (Figure 3.9 e & f). The continued decreases in toe-off distances were probably due to the shorter contact times, increased TD distances and increasing CM-h, which would have influenced the distance the centre of mass could move over the contact point. Furthermore, the more inclined trunk will have limited the clockwise rotation of the thigh and therefore the horizontal distance between the CM and the contact point. This decrease in toe-off distance represents an important factor limiting TD distances and therefore the propulsive forces of similar magnitudes compared to the initial acceleration phase. As sprinters commence their maximal velocity phase, further step-to-step changes in TD and toe-off distances, CM-h and segment orientation plateau. This shows parity with the suggestion by coaching literature (Crick, 2013f) where the maximal velocity phase is characterised by a consistent trunk orientation.

The changing kinematics through the different phases may have important implications for the performance of the sprinters. These were addressed further in Theme 2 (Technique analysis) and Theme 3 (Induced acceleration analysis). Since the step characteristic and kinematic changes identified in Theme 1 are largely driven by the work done at the joints, Theme 2 used an inverse dynamics analysis to investigate the changes in joint kinematics and kinetics between steps in the initial acceleration, transition and maximal velocity phases. This added to the conceptual understanding of the changing musculoskeletal characteristics as a sprint progresses.

Theme 2: **Technique analysis:** The aim of Theme 2 was to investigate the changes in joint kinetics between the initial acceleration, transition and maximal velocity phases. Theme 2 provided novel insights to improve the understanding of the changes in musculoskeletal demands as a sprint progresses and added valuable information to the growing body of knowledge of maximal sprinting. Based on Chapter 3, steps three, nine and 19 were selected to investigate the differences between these phases in more detail. An IDA was used to provide a joint kinetic analysis on the stance phases of steps three, nine and 19 within a group of sprinters. This provided the necessary data to address the research question of Theme 2:

# Research question (iii) - How do the joint kinematics and kinetics change between the initial acceleration, transition and maximal velocity phases?

The results of the between-step joint kinetic differences revealed some important differences between step three, nine and 19. At the MTP joint, the energy absorbed increased between steps three and nine and between steps three and 19 (moderate differences). This was due to an increased dorsiflexion angular velocity as the MTP dorsi-flexed over a larger ROM. Previous authors have suggested that performance during sprinting could be improved by minimising the negative work done by the MTP joint (e.g. Stefanyshyn & Nigg, 1997; Willwacher, König, Braunstein. Goldmann & Brüggemann, 2013). Smith et al. (2014) showed that dorsiflexion and dorsiflexion angular velocities at the MTP joint were significantly reduced while plantar flexor joint moments were increased when athletes wore sprint spikes versus barefoot conditions. From the results by Smith et al. (2014) it could be speculated that increasing longitudinal bending stiffness (LBS) may reduce the dorsiflexion ranges and dorsiflexion angular velocities which increased between steps three and nine and between step three and 19. However, this may be detrimental to the performance of sprinters especially at higher running velocities, as a stiffer MTP joint may restrict the sprinters' movement over the foot during the stance phases at higher velocities. In addition, Willwacher et al. (2013) identified a strategy where participants increased ground contact times as LBS increased. This may be detrimental to maximise velocity as low contact times are a feature of good performance during the maximum velocity phase (Weyand et al., 2000). While the differences between steps three, nine and 19 may be due to the increase in running velocity, further research is required to understand the influence of the reduction in negative work done at the MTP joint to performance across various running velocities.

The energy absorbed by the ankle plantar flexors increased from step three to step nine to step 19. The increase in energy absorbed at the ankle was achieved through a large increase in the dorsiflexion ROM at the ankle joint, which is consistent with data previously presented by Braunstein et al. (2013). However, the increasing ROM was associated with an increasing clockwise rotation of the shank. Previous results from Hunter et al. (2004c) showed that a plantar flexor ankle joint moment causes an anti-clockwise rotation at the shank. The increasing plantar flexor ankle moment and resulting energy absorbed at the ankle decelerated the clockwise rotation of the shank following touchdown (Chapter 4, Figure 4.18f). Previous studies have highlighted the importance of ankle stiffness (as determined by dorsiflexion ROM and ankle moment) when it comes to enhancing sprint performance during the first step (Bezodis et al., 2015) and maximal velocity phase (Nagahara & Zushi, 2016) in sprinting. The results suggest that controlling the relative rotation of the shank may be key to allow the rear foot to rotate over the contact point.

Chapter 4 revealed large increases in knee flexor and hip extensor moments at touchdown between step three and steps nine and between steps three and 19 (Figure 4.14 c & Figure 4.16 c). Combined with the increased touchdown knee flexor angular velocities between steps three, nine and 19, these joint moment changes may be representative of a more active touchdown as the participants attempted to minimise the horizontal foot velocity relative to the CM before touchdown. The relative horizontal velocity of the foot decreased from steps three  $(-5.36 \pm 0.80 \text{ m} \cdot \text{s}^{-1})$ to nine (-6.41  $\pm$  1.00 m s<sup>-1</sup>) to 19 (-7.14  $\pm$  1.00 m s<sup>-1</sup>). However, the larger knee flexor and hip extensor moments on steps nine and 19 may have also resulted in response to increased knee extensor and hip flexor moments generated by the increased GRFs and influenced by larger TD distances (Sun et al., 2015). Previous research (Mann & Sprague, 1980) has proposed that the presence of a hip extensor and knee flexor moment after touchdown would allow sprinters to minimise braking impulse by accelerating their body over the support foot. Indeed, the knee flexor moment at the start of ground contact during steps nine and 19 generated work, which represents a flow of energy from the muscle to the leg (Schache et al., 2011). This was explored further in Theme 3 (Chapter 5). While this may help reduce the braking forces experienced at higher velocities, these larger touchdown hip extensor and knee flexor moments may predispose the hamstring muscles to a larger risk of injuries (Mann & Sprague, 1980; Sun et al., 2015) during the transition and maximal velocity phases.

The moderate increases in knee extensor moment from step three to nine and 19 were probably due to an increasing need to assist the ankle plantar flexors in preventing the collapse of the shank following touchdown (Hunter et al., 2004) and limiting the loss in CM-h by minimising knee flexion (Johnson & Buckley, 2001). Especially during steps nine and 19, the knee extensor moment played an important role in maintaining CM-h by resisting knee flexion. This was emphasised by the appearance of a negative power phase while a knee extensor moment was active during steps nine and 19. Interestingly, when comparing the total work done at the knee while a knee extensor moment was active, no clear between-step differences were identified. This suggests that while the functional role of the knee extensor during first half of contact differs between the initial acceleration, transition and maximal velocity phases, that the capacity of the knee extensors to do work does not change. Although the knee moments were smaller compared to the ankle and hip joint moments, the knee extensors should be conditioned to generate and absorb energy as this allows them to fulfil the different functional roles during a sprint.

Theme 2 revealed that during the second half of stance, differences in GRF, joint kinematic and joint kinetic variables were generally small between steps three, nine and 19. Instead, the results of Theme 2 suggest that increasing braking impulses (via increasing braking forces and braking phase durations) and moderate to large changes in joint kinetics during the braking phase of ground contact were the main reasons for the differences in external GRF and CM acceleration observed between steps three, nine and 19. This highlights the increasing importance of the sprinters' "front side mechanics" (Mann, 2007, p. 86) as velocity increases and the sprinters posture becomes more inclined. While the results of Theme 2 provided an important insight of the joint kinematic and kinetic changes as a sprint progresses, based on this analysis alone, it is difficult to intuitively predict how the results identified in Theme 2 influence changes in CM translation, which is ultimately dependent on the segment rotations generated by moments at the joints. Furthermore, due to dynamic coupling of the multi-articulated systems, forces acting on one segment affect the

acceleration of all segments within the system (Zajac, 2002). Therefore, Theme 3 (Induced acceleration analysis) investigated how the changes in joint moments and segment orientations contributed to the changes in CM accelerations that were identified in Theme 1: Phases analysis (Chapter 3) and Theme 2: Technique analysis (Chapter 4). Theme 3 investigated the influence on the changes in CM acceleration (both magnitude and direction) during steps three, nine and 19.

Theme 3: **Induced acceleration analysis:** The final theme of this thesis aim to investigate the effects different forces (joint moments and non-biological) acting on a sprinter have on the sagittal plane acceleration of the sprinter during steps from different phases of a sprint. By building on the knowledge gained from Themes 1 and 2 of this thesis, Theme 3 developed a greater depth of knowledge regarding the underlying mechanisms by which sprinters accelerate their CM during steps from different phases of a sprint. This was achieved by quantifying the contributions to whole-body and segmental CM accelerations through an IAA (Zajac, 2001). The knowledge gained from Theme 3 helped developed a better conceptual understanding of the link between technique and performance of the sprinter within the initial acceleration, transition and maximal velocity phases. Considering the differences in joint kinetics and segment orientations between steps three, nine and 19 as identified in Theme 2, the following research question was addressed.

# Research question (iv) – What are the primary contributors to the acceleration of the CM during the initial acceleration, transition and maximal velocity phases?

The largest contributors to CM acceleration were the joint moments and the accelerations at the foot-floor interface. The absolute backward and upward induced acceleration resulting from the accelerations at the foot-floor interface increased between the three steps analysed and contributed to  $-0.01 \pm 0.01 \text{ m} \cdot \text{s}^{-1}$  (145%),  $-0.05 \pm 0.01 \text{ m} \cdot \text{s}^{-1}$  (68%) and  $-0.08 \pm 0.02 \text{ m} \cdot \text{s}^{-1}$  (47%) of the braking impulse on steps three, nine and 19 respectively. This coincided with an increasing forward and downward velocity of the foot prior to touchdown, which was reported in Chapter 4 (Table 4.4). Indeed, results from Theme 3 showed that the linear deceleration of the foot following touchdown contributed to 125%, 101% and 101%

of the braking impulse induced by the accelerations at the foot-floor interface. In Theme 2 (Chapter 4), the increasing braking impulse due to the increased braking forces and the increased duration of the braking phase was suggested to be the main reason for the decreasing net horizontal impulse between steps three, nine and 19. These results support previous suggestions (e.g. Hay, 1994; Mann, 2007; Seagrave et al., 2009) that sprinters should reduce the horizontal velocity of the foot prior to touchdown. Coaches should therefore strive to encourage sprinters to minimise the forward and maximise the downward velocity of the foot prior to touchdown. This can be achieved by emphasising a large backward angular acceleration of the thigh relative to the trunk (Seagrave et al., 2009). Especially at higher running velocities, this will help to minimise braking and increase vertical ground reaction forces over the first 0.03 s of stance.

Of the joint moments investigated in Theme 2 (Chapter 4), the ankle plantar flexor moment induced the largest forward and upward acceleration on the CM. Interestingly, the ankle plantar flexor moment induced a negative horizontal impulse on the CM during the braking phases of steps nine  $(-0.01 \pm 0.01 \text{ m} \text{ s}^{-1})$  and 19  $(-0.04 \text{ m} \text{ s}^{-1})$  $\pm 0.02$  m s<sup>-1</sup>), which was not the case during step three (Figure 5.3; Table 5.3). The more inclined shank and trunk (Figure 5.6) and increases in TD distances between steps three, nine and 19 will have caused the backward orientated GRF vector induced by the ankle plantar flexor moment following touchdown. These results highlight the importance of posture in dictating the direction of the GRF vector and support the suggestion by the British Athletics coaching literature (Crick, 2013e) that smaller touchdown shank angles and smaller CM angles are favourable to generating larger propulsive forces. While the instantaneous orientation of the sprinter ultimately determines the orientation of force generation during stance, excessively large between-step increases in touchdown distance (via large increases in shank and trunk angles) will result in large increases in braking impulses during subsequent steps.

The knee flexor moment following touchdown induced a forward acceleration on the CM. The magnitude of this forward induced acceleration increased from step three to nine and 19 as the knee flexor moment increased between steps three and nine and three and 19 (Chapter 4). The larger knee flexor moments presumably started

during late swing as the knee flexors performed negative work to reverse the motion of the shank and foot prior to touchdown (Nagahara et al., 2017) increasing the backward and downward velocity of the foot prior to touchdown (Table 4.4). However, the increased TD distance will have also contributed to the increased knee flexor moments (Sun et al., 2015) and this larger knee flexor moment during steps nine and 19 resulted in a larger forward acceleration induced on the CM following touchdown, which suggests that a knee flexor moment has potential benefits to performance. However, caution is advised as an increased amount of negative work done at the knee during terminal swing (Chumanov, Heiderscheit, & Thelen, 2007) and a large hip extensor and knee flexor moment around touchdown may predispose the sprinter to an increase risk of hamstring injuries (Mann & Sprague, 1980; Sun et al., 2015). Sprinters therefore need to be adequately conditioned to cope with the increased demand placed on the hamstring muscles while also ensuring their TD distances are effectively minimised to reduce their influence on knee flexor moments and braking forces.

During mid-stance, the knee extensor moment induced the second largest upward accelerations on the CM, which supports the suggestion by Johnson and Buckley (2001) that the knee extensor moment plays an important role in maintaining CM-h. However, the larger knee extensor moments and more upright postures associated with steps nine and 19 did not translate into larger upward CM accelerations compared to step three (Figure 5.4c & Figure 5.5e). A knee extensor moment is therefore reliant on the plantar flexors of the ankle and MTP joints to stabilise the shank and rear foot segments in order to accelerate the sprinter forward and upwards. The joint moments of the hip induced relatively small accelerations on the CM. This suggests that while the hip extensors induced large backward accelerations at the thigh and forward accelerations at the HAT, the overall contribution to centre of mass acceleration is limited by the capacity of the joint moments at the knee and ankle to transfer these accelerations to the ground and therefore contribute to the acceleration of the centre of mass. A holistic strength-training program that places equal emphasis on the development of muscles crossing the hip, knee and ankle is important to success in sprinting.

To investigate the effect that different joint moments had on the different segments of the model (i.e. rear foot, shank, thigh and HAT), three force events present in all three steps were identified and investigated in more detail. The resulting segmental induced accelerations by the different joint moments were determined at those events. This provided the necessary data to address the second research question of Theme 3: Induced acceleration analysis.

# Research question (v) - Why do the segmental accelerations induced by the different joint moments change between the initial acceleration, transition and maximal velocity phases?

The investigations of Chapter 5 revealed important couplings between proximal and distal joint moments. At the peak braking force event (Figure 5.6) presented in Chapter 5, the FC plantar flexor moments at all steps and to a lesser extent the knee flexor moment on steps nine and 19 opposed the backward and downward acceleration induced by the hip extensor moments. Although the accelerations induced by the FC plantar flexor and knee flexor moments were consistently opposite to those of the hip moments, the direction and magnitudes of the resulting induced acceleration vectors became more inclined (i.e. more vertically orientated) between steps three, nine and 19. The results of figure 5.6 highlight how the orientation of the sprinter influenced the direction of the induced accelerations while the magnitude of the moments determined the size of the induced accelerations.

The data from figure 5.6 also revealed that the backward acceleration induced on the CM by the FC plantar flexor moments during steps nine and 19 was due to an increasing backward orientated acceleration induced on the upper body and more vertical acceleration induced on the stance leg segments. This resulted from the increasing shank and trunk angles, which increased the TD distances between steps three, nine and 19. Minimising TD distances and slowing the step-to-step increases in shank and trunk angles may therefore represent an important mechanism to decrease the braking forces generated by the FC plantar flexor moments at the beginning of ground contact. At the peak vertical force event, both the hip extensor and knee extensor moments contributed to the upward acceleration on the CM. However, these were dependent on the ability of the FC plantar flexor moment to induce large upward accelerations on the rear foot to ensure a fixed rear foot to allow the hip and knee extensors to provide support to the upper body. When acting in isolation, the hip and knee extensor moments were therefore not able to increase the upward acceleration of the CM (Figure 5.5e) despite the more vertical orientation of the segments (Figure 5.7) and larger knee extensor moments in steps nine and 19.

Through addressing research question v, an important dual role of the plantar flexors of the FC was revealed. Firstly, during the first half of stance, the plantar flexor played an important role in generating a fixed foot and shank segment by opposing the accelerations induced by the more proximal joint moments (Figure 5.6 & Figure 5.7). This links to the importance of ankle stiffness identified by Bezodis et al. (2015) during the first step of a sprint and Nagahara and Zushi (2016) during the maximal velocity phase. A stiff ankle joint, which could be achieved through an increased plantar flexor ankle moment and increased pre-activation of the muscles surrounding the ankle joint (Mero & Komi, 1987) at touchdown, would provide a stable foot and shank to allow accelerations generated by the proximal joint moments to translate the upper body forwards and upwards. Secondly, as the participants approached toe-off, the FC plantar flexor moments induced a forward and upward acceleration on the upper body and stance leg (Figure 5.8) during steps three, nine and 19. This shows parity to the results previously reported that the ankle plantar flexors are the primary contributors to the propulsion of the CM during fast walking (Liu et al., 2008) and running over a range of velocities between 2.00 -5.00 m s<sup>-1</sup> (Hamner et al., 2013). Coaching literature suggests that this plantar flexion of the ankle towards toe-off represents a recycling of the stored elastic energy, which generates vertical centre of mass velocity and re-accelerates the foot following the braking phase (Crick, 2013d). The results of the current study provide evidence that the plantar flexor moment at the ankle and MTP is the primary source that increases the forward and upward energy of the whole body during the propulsive phase of stance (Figure 5.2; Figure 5.8). This supports the suggestions by coaching literature (e.g. Crick, 2013d) and emphasises the importance of a powerful plantar flexion about the ankle and MTP joints as sprinters approach toe-off.

The thematic framework, which utilised a mixed methods approach consisting of empirical and theoretical research, provided a meaningful contribution to knowledge and understanding of the underlying mechanics of sprinting. Theme 1 (Phase analysis) provided a better understanding of the different characteristics of the initial acceleration, transition and maximal velocity phases. Theme 2 (Technique analysis) identified specific differences in joint kinematics and kinetics between the three phases. Finally, through a more in depth interpretation of the results from Theme 2, Theme 3 (Induced acceleration analysis) contributed original knowledge concerning the changes in technical variables and their link to the changes in GRFs as the sprint progresses.

## 6.3 Discussion of Methodology

In this section, some key aspects of the methodologies used throughout the thesis will be discussed. This includes an assessment of the data collection methods to obtain the empirical data, aspects of the study design, determination of phases in maximal sprinting and the use of the IAA.

## 6.3.1 Assessment of data collection methods

When choosing the most appropriate data collection method for this thesis, it was important to choose a system that provided accurate data without interfering with the athlete and their execution of the movement. Furthermore, as data would be collected in a training environment it was essential that the data collection provided minimal interference with athletes training in the facility. As the sagittal plane motion of sprinting provides the most relevant information and medial-lateral forces are negligible (Rabita et al., 2015), it was decided that a 2D video-based approach was an appropriate means of collecting accurate and externally valid data from sprinting. To investigate Theme 1, a protocol involving high-resolution 50 Hz video (1440 × 1080 pixels) and wide fields of view were used to maximise the number of steps that could be captured per camera. The accuracy was found to be sufficiently good (horizontal: 0.005 m; vertical: 0.004 m) to provide confidence in the identification of changes between successive steps.

Due to the limitations of collecting data relating to specific events (e.g. touchdown and toe-off, step frequency) using 50 Hz video (Salo et al., 1997), a 200 Hz panning camera was used to collect the relevant temporal data. Data from the panning camera was retrospectively synchronised to that of the 50 Hz cameras, using linear interpolation between the two frames digitised at touchdown and toe-off. The relevant variables at touchdown and toe-off were therefore identified to within 0.002 s of the event. Linear interpolation was deemed appropriate to approximate touchdown and toe-off variables as a pilot study revealed sufficiently small differences in segment angle between data calculated using a cubic spline interpolation or linear interpolation.

To collect the empirical data for Themes 2 and 3 of this thesis, high-resolution video  $(1440 \times 1080 \text{ pixels})$  was collected at 200 Hz. Since data from only a single step at a time was required, narrower fields of view ensured that the resolution of measurement was sufficiently high when collecting data for the IDA and IAA analysis. A 4.000 × 1.900 m plane was calibrated in the centre of the field of view. This was wide enough to provide the necessary data for one step (touchdown to touchdown) plus additional frames before and after the step, while ensuring that the accuracy was increased (horizontal: 0.002 m; vertical: 0.002 m). Measures were taken to reduce the number of rejected trials. These include using two force plates in series, including trials where contact occurred across the two force plates and ensuring the distance between the starting blocks and force plates were pre-determined for each participant. Overall, only 24% of all collected trials were unable to be used for further analysis. This also allowed the number of trials per step to be kept to a minimum (~ 3) thus minimising the influence of fatigue on performance.

#### 6.3.2 Study design

A combination of multiple single-subject (Bates, 1996) and group design was used throughout this thesis. Theme 1 used a multiple single-subject design to identify step-to-step differences between the initial acceleration, transition and maximal velocity phases. This allowed the identification of a range of  $T_{start}$  (steps 4 to 6) and  $MV_{start}$  (steps 14 to 16) steps based on each participant's best trials. The

participants' best performances on each data collection day were used as they were regarded to represent higher performance throughout the phases compared to slower trials and were therefore selected as a more appropriate indication of the location of these breakpoint steps. The approach of using the best trial was adopted in Chapters 4 and 5 to fulfil the aim of understanding changes in kinematics and kinetics during a maximal sprint throughout all sprint phases.

For Themes 2 and 3, a cross-sectional repeated measure group-based study design was selected to investigate the changes between the initial acceleration, transition and maximal velocity phases within a group of 13 well trained sprinters. The magnitude of the differences in key variables between single steps within each phase were quantified via effect size statistics, and the meaningfulness of these differences was determined using magnitude-based inferences (Batterham & Hopkins, 2006). This provided an indication of the meaningfulness of the observed differences in the context of the smallest worthwhile difference, and therefore provided an objective and applied means through which to understand changes in technique between the initial acceleration, transition and maximal velocity phases. There were, however, large standard deviations within some variables reported in Chapters 4 and 5. Although the meaningfulness of the between step differences across the participants were quantified using effect size statistics and magnitude-based inferences, the large standard deviation reported in Chapters 4 and 5 suggest individual strategies which may have been masked by grouping the data. However, while investigating individual differences was beyond the scope of this thesis, a future area of study could investigate individual differences between steps as a sprint progresses.

Due to availability of only two force plates, an obvious delimitation of Themes 2 and 3 is that the data for steps three, nine and 19 was collected from separate trials. However, the similarities of the step characteristic and kinematic touchdown and toe-off data from Chapter 4 compared to the relevant data from Chapter 3 and previous studies (e.g. Nagahara, Matsubayashi et al., 2014) provided sufficient confidence that steps three, nine and 19 were representative of steps that occurred in the initial acceleration, transition and maximal velocity phases of sprinting. Furthermore, the identification of the best trials ensured that the steps that more

closely represented individual maximal performance were selected. The detailed IDA and IAA analysis presented in Chapter 4 and 5 was therefore relevant to increase understanding of the changes in musculoskeletal demands associated with the initial acceleration, transition and maximal velocity phases and therefore address Themes 2 and 3.

### 6.3.3 Determination of phases in maximal sprinting

This identification of the delimiting steps of the initial acceleration, transition and maximal velocity phases was an important aspect of this thesis. Therefore, the identification of these phases formed part of Theme 1. Because the start of the transition phase ( $T_{start}$ ) and maximal velocity phase (MV<sub>start</sub>) occurred at different steps between sprinters and between different trials of the same sprinter, it was decided to identify a range of  $T_{start}$  and MV<sub>start</sub> steps based on the participants' best trials. These ranges were then used to identify the steps occurring in the initial acceleration, transition and maximal velocity phases. The analysis used in Theme 1 (Chapter 3) and the identification of a range of  $T_{start}$  and MV<sub>start</sub> steps provided confidence that steps three, nine and 19 analysed in Theme 2 (Chapter 4) and Theme 3 (Chapter 5) would occur in the initial acceleration, transition and maximal velocity phases. This was later confirmed by retrospectively comparing the data from steps three, nine and 19 to data from Theme 1 (Chapter 3).

## 6.3.3 Induced acceleration analysis

The use of IAA and IPA in Chapter 5 proved a valuable tool that enabled a more in-depth interpretation of the underlying relationship between the joint moments calculated in Theme 2 with the changes in CM acceleration between steps three, nine and 19. Whilst it must be emphasised that certain assumptions were made regarding the planar spatial model and foot-floor contact model used in Chapter 5, the comparison between the measured and calculated GRF revealed a close match (RMSD:  $11 \pm 2$  to  $34 \pm 11$  N or  $1 \pm 0$  to  $3 \pm 1\%$  of the force excursion). This provides evidence of the appropriateness of the model and is a necessary condition for accurate induced acceleration results (Hamner et al., 2010). However, while the results of Chapter 5 revealed acceptably low errors in the calculated GRF, these do not necessarily reflect the validity of the IAA results (Dorn et al., 2011).

When considering the influence of the foot model (i.e. one vs. two-segment foot) and foot-floor contact model (single vs. multi-contact points) a pilot study revealed (Appendix A6) that the errors between the measured and calculated GRFs were generally low across the different models used while the resulting contributions by the ankle and MTP moments differed considerably. While this further highlighted the sensitivity of the IAA to the model in the analysis (Chen, 2006), it did show that the overall level of detail within a model is ultimately dependent on the question. For example, if the question was to understand the contribution by the FC as a whole, then a simple one-segment foot model connected to the ground via a single contact joint may be sufficient to address the aim. However, in Chapters 4 and 5, the aim was to include the MTP joint in the investigation. Therefore, a two-segment foot and multi-point contact model was required to provide the extra level of model detail to address the aim of the chapter.

Previous research has shown that the errors associated with modelling the foot-floor interaction can have an important influence on the results of an IAA (Koike et al., 2017). In Theme 3, the use of the COP in the foot-floor model at the start and end of ground contact could explain the larger errors in approximating the ground reaction forces at touchdown and toe-off. This could be linked to the relatively large fluctuations in COP positons when GRFs are low (Koike et al., 2017). Future studies could investigate ways to better model the foot-floor contact points by optimally treating the COP data or identifying virtual point along the foot were contact can be defined (Koike et al., 2017). Nonetheless, the foot-floor model used in Chapter 5 provided sufficient accuracy allowing the GRFs to be approximated to within 3% of the measured GRFs.

Compared to the spatial model used in previous IAA studies (e.g. Patel et al., 2007; Dorn et al., 2012; Hamner et al., 2010; Koike & Nagai, 2015), the planar five segment model could be considered relatively simple. Since the stance leg can be considered the major contributor to performance during the ground contact, the model in Chapter 5 was selected to closely represent the sagittal plane motion of the stance leg (via the inclusion of an MTP joint) and ground contact (via the use of a multi-point foot-floor contact model). The pelvis, trunk, head and arms were modelled as a single segment (i.e. HAT) and therefore assumed to rotate as one. While simpler models may express the results of an IAA differently to more complex models (Chen, 2006), models should represent a valid simplification of reality (Hatze, 2002) and should be as simple as possible while appropriately addressing the purpose of the research (Yeadon & King, 2008). The results derived from the IAA using the spatial and foot-floor models therefore are considered sufficiently accurate (relative RMSD between  $1 \pm 0$  to  $3 \pm 1\%$  of the force excursion) to represent the motion under investigation and address the research questions of Theme 3 of this thesis. Furthermore, the repeated measures design of Themes 2 and 3 means that the differences observed would have represented actual differences between the steps as other confounding factors (e.g. data collection and processing methods) were controlled throughout.

The results of the IAA and IPA provided an important starting point to assess the contributors to CM acceleration during steps three, nine and 19. While these results should be interpreted in the context of the IAA performed in Chapter 5 and the aim of this thesis, the results provided some important insights into the changes in contributions to CM acceleration between steps three, nine and 19. Furthermore, the IAA results in Chapter 5 were within a reasonable level of agreement with those that have previously investigated the contributions of joint moments in sprinting (e.g. Koike & Nagai, 2015) despite different spatial and foot-floor contact models being used in the analysis.

## 6.4 Novel contributions to knowledge and practical implications

To increase the knowledge and understanding of the changes associated with acceleration up to the maximal velocity phase, a thematic approach based on three main themes was used (Phase analysis, Technique analysis, Induced acceleration analysis). These themes identified phases within maximal sprinting and investigated the differences between those phases. Compared to the number of studies that have investigated the biomechanics of sprinting, relatively few studies have previously reported step-to-step kinematic changes across multiple steps (e.g. Čoh et al., 2006; Nagahara, Naito, Morin & Zushi, 2014; Nagahara, Matsubayashi et al., 2014). Research question 1 of Theme 1 compared different measures that were previously used to identify the start of the transition and maximal velocity phases. The results showed that breakpoints in sprinting that were identified using segment

angles (i.e. shank and trunk angles) as suggested in British Athletics coaching literature (Crick, 2013a) provided similar ranges of steps when compared to using CM-h to identify breakpoints. However, the within-trial comparison showed step differences of up to 2.3 steps between segment angles and CM-h. While this suggests that using shank and trunk orientations may be appropriate to provide simple feedback in applied settings, measures based on segment angles only provide information about what is happening locally at the segments. Therefore, for research purposes, a measure of whole body changes (i.e. CM-h) may be more beneficial. Overall, the results from Theme 1 (Chapter 3) show that maximal sprints up to 5 to 10 m should be used to develop the initial acceleration phase and maximal sprints between 20 to 35 m could be used to develop the transition phase combined with the initial acceleration phase.

As highlighted in the conclusion of Theme 1 (Chapter 3), specific kinematic changes were identified in the different phases. These included large step-to-step changes in kinematic variables (especially shank angles and touchdown distances) during the initial acceleration phase compared to the transition phase while trunk angles increased throughout the initial acceleration and transition phases and plateaued during the maximal velocity phase. The results of Theme 1 (Phase analysis) increased knowledge of step-to-step changes in the variables more accessible to coaches and sport scientists that are associated with the initial acceleration, transition and maximal velocity phases in sprinting. Better knowledge of the characteristics of these phases could ultimately allow coaches and sport scientists to evaluate specific training drills to ensure they reflect the requirements of the steps being developed while also facilitating the evolution of posture that occurs or is desired in sprinting.

By combining an IDA and IAA, Themes 2 (Technique analysis) and 3 (Induced acceleration analysis) provided meaningful insights into the changing musculoskeletal characteristics and their contributions to performance between the initial acceleration, transition and maximal velocity phases. This had not previously been demonstrated across steps from different phases in sprinting. As demonstrated in Chapter 4, the increasing relative braking impulse (due to a longer braking phase and larger braking forces) between steps three, nine and 19

represents an important limiting factor influencing the large decreases in net horizontal impulse between the three steps. The increasing braking phase durations from steps three to nine to 19 was accompanied by an increased energy absorption at the knee and ankle joints. Furthermore, the increased ROM over which energy was absorbed resulted from an increased clockwise rotation of the shank relative to the motion of the thigh and foot segments. This may be important to consider when selecting training drills to best condition the plantar flexors and knee extensors to absorb energy. Coaches may need to consider the increased forward rotation of the shank relative to the foot that was identified during the transition and maximal velocity phases when selecting specific exercises to develop the ankle plantar flexor and knee extensor abilities to absorb energy during ground contact. This could be achieved by using modified strength exercises, repeated jumps with a horizontal emphasis (Bosch & Klomp, 2005; Schiffer, 2009) or sprinting with added external load (Seagrave, 1996). Furthermore, horizontally orientated plyometric drills involving a deliberate pause on landing could be used to focus on developing the ankle plantar flexors and knee extensor ability to absorb impact forces (Gambetta, 2007).

During the second half of stance and approaching toe-off, the joint kinematic and kinetic differences between the steps were smaller. This suggests that joint kinetics may not necessarily represent a limiting factor to generating comparable propulsive forces between steps three, nine and 19. Rather, the sprinters' posture (segment orientations) and shorter toe-off distances influenced the decreasing propulsive forces between steps three, nine and 19. These decreasing propulsive forces between the initial acceleration, transition and maximal velocity phases may therefore be inevitable, and trying to generate larger forces during the latter half of stance may have a detrimental effect on performance at higher velocities. These results add new evidence to support the importance of a sprinters 'front side mechanics' (Mann, 2007' p. 86) which emphasises the mechanics occurring in front of the CM during terminal swing and early stance as the most important factor determining performance during maximum velocity sprinting.

A novel result presented in Chapters 4 and 5 is that the increasing braking impulses identified in Chapter 4 resulted from increasing forward velocities of the foot relative

to the ground prior to touchdown and the increasing touchdown distance and changing posture between steps three, nine and 19. Although these factors have been previously linked to braking impulses in sprinting (Hay, 1994; Hunter et al., 2005), the results of Chapter 5 quantified the amount of braking impulse that could be directly attributed to these factors. Firstly, a major contributor to braking impulse following touchdown was the acceleration at the foot-floor contact point, which largely resulted from the deceleration of the foot at touchdown. Secondly, the increasingly larger braking impulses identified between steps three, nine and 19 (Chapter 4; Table 4.6) were influenced by the larger touchdown distances, which resulted from larger shank and trunk angles relative to forward horizontal. This can be visualised in figure 5.3, figure 5.6 and figure 5.7. These figures show that as the posture of the sprinters became more inclined between steps three, nine and 19 (due to larger shank and trunk angles), the joint moment induced centre of mass accelerations (e.g. ankle plantar flexor moment; Figure 5.3, Figure 5.5d) also became more inclined. This builds on the work by Bezodis et al. (2015) who theoretically demonstrated that decreasing touchdown distances during the first step of a sprint could increase performance. Although the magnitude of the joint moments influence the magnitude of the resulting accelerations, the posture of the system will influence the direction of the resulting accelerations (Hof & Otten, 2005). Therefore, while the forces and joint moments acting on the system ultimately determine the magnitude of the induced accelerations identified in Chapter 5, the orientations of the segments and positioning of the segments relative to the contact point determine the direction of those induced accelerations. Furthermore, these findings build on the work by di Prampero et al. (2005), Kugler and Janshen (2010) and Rabita et al. (2015) providing further evidence of the importance that the sprinter's posture plays in influencing the orientation of the GRF vector. Although the step-to-step changes in posture during maximal acceleration are inevitable, future studies could investigate coaching interventions and specific training drills that could be used to encourage sprinters to alter their posture within specific phases, with a view to investigating how to enhance performance and decrease injury risk. This supports the practice of year round technical training to ensure sprinters are able to achieve the correct positions necessary for optimal performance.

A new finding from Theme 3 (Chapter 5) was the increased contribution to the overall horizontal impulse by the centripetal accelerations at the joints of the stance leg. This was also previously reported at lower steady state running velocities (Hamner et al., 2013). While the contributions in steps three and nine were relatively low (i.e. ≤10%), in step 19 the angular accelerations contributed 57% to the total horizontal impulse. These results suggest that during the maximal velocity phase, clockwise velocities (when performance is viewed from left to right) of the thigh, shank and foot play an important role in contributing to overall performance during stance. Sprinters should attempt to generate these angular velocities during the terminal swing phase and ground contact phase. This could be achieved by increasing the positive hip extensor work and negative knee flexor work during the terminal swing phase by accelerating the leg backward and downward relative to the upper body. However, it is worth noting that increasing the negative work done by the knee flexors during the terminal swing phase has previously been reported as a risk factor to hamstring injury (Chumanov et al., 2007). Sprinters therefore need to be physically conditioned to cope with the increased demand placed on the hamstring muscles when implementing this technical focus.

Increasing the angular velocity of the thigh and shank prior to touchdown may have the added benefit of minimising the horizontal velocity of the foot prior to touchdown, minimise touchdown distances and ensuring hip extensor and knee flexor moments are sufficiently large at touchdown to accelerate the sprinter over their contact point following touchdown (Mann & Sprague, 1980). An original finding from Chapter 5 was the forward induced acceleration on the CM due to the knee flexor moment at touchdown, which increased from steps three to nine, and 19 (Chapter 4; Figure 4.14c). Although, these results provide evidence to support the suggestion by Mann and Sprague (1980) that a knee flexor moment following touchdown accelerates the CM forwards over the contact point, a more important finding was the knee flexor moments role in transferring thigh accelerations which were induced by the relatively larger hip extensor moment to the shank. This would oppose a backward motion of the knee and therefore contribute to accelerating the hip and upper body over the contact point (Figure 5.6: steps nine and 19). Increased horizontal force application has previously been linked to an appropriate coordination between hip and ankle moments during stance (Rabita et al., 2015). The results of Chapter 5 highlighted how different joint moments work together to induce different accelerations on the segments, which allows the sprinter to accelerate the whole body in a way that could not be achieved by one joint moment alone. Together these different contributions combined to allow the sprinters to perform the skill. The analysis of Chapter 5 revealed that the hip and knee extensor moments have the ability to induce relatively large accelerations on the segments. These however rely on the ability of the FC plantar flexor moments to provide a stable foot and shank to transfer these accelerations to the ground. These results provide some mechanistic explanation supporting the use of dynamic conditioning exercises like heavy sled sprinting (e.g. Morin et al., 2016) that encourage the generation of large extensor joint moments at the proximal joints and dynamically overload the FC plantar flexors. This will develop the FC joint plantar flexors' ability to transmit the accelerations generated by the hip extensors more effectively.

#### 6.5 Directions of future research

The work throughout this thesis has highlighted some potential avenues of future work. These can be divided into four categories namely: methodology, future research of sprint mechanics, training studies and additional applied research questions.

#### Methodology

A delimitation highlighted in section 6.3.2 was that the empirical data collected for Chapter 4 to compare between steps three, nine and 19 was collected from separate trials. The recent emergence of multi force plate systems (e.g. Nagahara et al., 2017a) means that kinematic and kinetic data can be collected across multiple steps from the same trial. This could provide some unique insights into the mechanics of sprinting. However, these systems are not readily available worldwide, and there is precedent for combining data from separate trials (Rabita et al., 2015). To the author's knowledge, the approach adopted in this thesis was the first of its kind to compare joint kinetics and contributions to CM motion across steps from the initial acceleration, transition and maximal velocity phases of sprinting.

#### Future research of sprint mechanics

While the thesis has focused on understanding the differences between the initial acceleration, transition and maximal velocity phases, future work could also consider investigating the characteristics of the T<sub>start</sub> and MV<sub>start</sub> breakpoints steps. While the results of Chapter 3 and the recent work by Nagahara, Matsubayashi et al. (2014) and Ettema et al. (2016) have added to the understanding of the acceleration phase, there is still some uncertainty regarding these breakpoint steps. Specifically, it remains unclear whether they are a characteristic of maximal sprinting or reflect an imperfection in performance (Ettema et al. 2016). Nevertheless, three separate studies have identified a T<sub>start</sub> step (Nagahara, Matsubayashi et al., 2014; Ettema et al., 2016; Chapter 3) in a similar location in at least some sprint trials. This event therefore warrants further investigation to understand why it occurs and what the implications of it are for sprint performance.

The use of IAA provided a powerful tool to develop the knowledge gained from the IDA alone. The findings that emerged from Theme 3 highlighted the importance that accelerations at the contact point and posture have on the generation of horizontal and vertical GRF. While beyond the scope of the current thesis, one potential area of future research is to implement a sensitivity analysis to identify how systematic changes in different variables (e.g. joint moments, segment orientations, acceleration at the contact point) influence the results of the IAA. These results could then be used as a precursor to inform future technical interventions or to developing more complete forward dynamic simulations of sprinting. The results of such a forward dynamics analysis could provide a more in-depth understanding of the influence that certain technical changes may have on sprint performance.

The addition of EMG to the analysis of differences in technique between phases of sprinting can provide additional understanding of differences in muscular activation strategies during a sprint. These data can be used to supplement a joint kinetic analysis in sprinting or combined with kinematic and kinetic data to develop a musculoskeletal model that allows the estimation of muscle contributions to motion. Furthermore, the data of the current thesis is based on a cross-sectional study design. While this increased the understanding of the biomechanical differences between different phases of sprinting, a longitudinal approach would further our

understanding of the key mechanical variables that are associated with changes in performance over time. This would provide further evidence of which factors should be addressed in athlete development.

#### Training studies

The results of the current thesis have highlighted some important practical implications, which could have direct impact on a sprinters performance. Firstly, the importance of horizontal foot velocities and touchdown distances on the generation of braking impulses during stance have suggested an important avenue to enhance performance during the transition and maximal velocity phases of sprinting. Secondly, the importance of the sprinter's body orientation plays in the forces they ultimately generate has been highlighted by the results of this thesis. Future training studies investigating how these mechanics can be tailored to minimise braking forces and increase performance during different phases of sprinting will have important real world applications. These interventions could range from identifying effective cueing strategies (i.e. internal vs. external focus of attention; e.g. Bezodis, North & Razavet, 2017) to investigating the inclusions of specific drills (e.g. wicket runs; Altis World, 2015) which develop a sprinter's 'front side mechanics' (Mann, 2007, p. 86).

#### Additional applied research questions

Apart from the questions that were addressed in this thesis, additional questions can be addressed with the extensive data set collected over the course of this PhD. Firstly, although only the fastest trials were analysed in the current thesis, interesting questions could be addressed relating to the differences between faster and slower trials within and between participants. For example, the questions 'are faster trials associated with less inclined body orientations?' and 'how do between-step changes associated with the initial acceleration, transition and maximal velocity phases compare between slower and faster trials?' would contribute to our understanding of the results discussed in the current thesis. Secondly, the ideas presented in this thesis are based on the theoretical principle that the body orientation determines the orientation of the external ground reaction forces vector (e.g. di Prampero et al., 2005; Hof & Otten, 2005; Ettema et al., 2016). However, it is still unclear how specific segment orientations relate to the orientation of the ground reaction force. For

example, addressing the question 'do sprinters with larger horizontal force exhibit smaller trunk and/or shank angles?' may increase understanding of specific segment orientation and kinematics related to better force application. Finally, changes in joint or segment coordinative patterns between steps three, nine and 19 may provide additional insights into the movement strategies used by sprinters during different phases of sprinting.

### 6.7 Thesis Conclusion

The aim of this thesis was to investigate biomechanical differences in technique between the initial acceleration, transition and maximal velocity phases of a sprint. This aim was addressed by constructing three research themes (Phase analysis, Technique analysis and Induced acceleration analysis) and their associated research questions. By dividing the acceleration phase in sprinting into initial acceleration, transition and maximal velocity phases, important inter-step differences were identified in the step-to-step changes in postural variables between the phases (Theme 1). Theme 2 investigated the differences between a step from the initial acceleration, transition and maximal velocity phases, which allowed the identification of important joint kinetic differences during the braking phase of ground contacts. Finally, Theme 3 built on the knowledge gained from IDA analysis of Theme 2 by investigating the changes in contributions to CM accelerations between steps three, nine and 19.

Overall, through a combination of inverse dynamic and induced acceleration analysis, a more in-depth understanding of the changing musculoskeletal characteristics and their influence on performance during the initial acceleration, transition and maximal velocity phases was gained. The research presented in this increased the conceptual understanding of the kinematic and thesis musculoskeletal changes between steps across different phases in sprinting. Coaches can use this information to inform specific aspects of their training and evaluate specific exercises and drills to assist with the preparation of the athletes they coach for the challenges associated with the different phases of a sprint. Specifically, the Phase analysis (Theme 1) provided insights into the characteristics of the phases based on variables that are more visually accessible to coaches. The knowledge gained could help assess specific drills used to develop specific movement patterns associated with the different phases in sprinting and to facilitate the step-to-step development of the sprinters posture throughout the phases. The Technique analysis (Theme 2), using an IDA, identified trends between braking impulses and foot velocities and between braking impulses and touchdown distances across three phases in sprinting. Furthermore, specific differences pertaining to the negative and positive work done at the joints of the stance leg, and provided some unique insights into the changing musculoskeletal demands of maximal sprinting. Building on the results of Theme 2, the Induced acceleration analysis (Theme 3) contributed original knowledge by revealing how changes in posture influences the orientation of ground reaction forces. Furthermore, Theme 3 showed that a major component of the braking forces at touchdown were induced by the deceleration of the foot at touchdown.

The work of this Thesis developed the conceptual understanding of the technical differences between steps from different phases. This increased understanding could facilitate the development and evaluation of specific exercises or drills that address the challenges associated with the biomechanical changes between the phases of maximal sprinting. Specifically, the results of this Thesis highlighted important changes during the braking phase of ground contact as a sprint progresses. Therefore, throughout the durations of a sprint, sprinters should emphasis the development of the leg mechanics during the terminal swing and early stance phases to ensure step-to-step changes in braking impulses are managed.

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# Appendix A - Overview

# Appendix A provides additional data relating to Chapters 3 to 5.

# Chapter 3:

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# Chapter 4:

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## Appendix A1- Reliability and objectivity of digitising

## Introduction

To assign value to the associated uncertainties within the digitising process, reliability and objectivity of the digitising was determined. One way to make sense of the level of reliability necessary to provide meaningful data is to compare the level of uncertainty associated with digitising to the between trial standard deviation or to the range over which a variable changes throughout a trial.

#### Method

One trial from the data collected in Chapter 3 was digitised three times by two experienced digitisers. Each re-digitisation included identifying the touchdown and toe-off events in the panning camera as well as digitising two frames around touchdown and toe off in the static cameras, to replicate the methods of Chapter 3. Data from this was then used to calculate the within-digitiser (reliability) and between-digitiser (objectivity) differences in step velocity, step length, step frequency, trunk angles, thigh angles, shank angles, CM-h, contact distance and the frames identified as touchdown and toe-off. In digitising, reliability refers to the ability of an individual digitiser to consistently identify the same landmarks, while objectivity referrers to the consistency between digitisers in identifying the same landmarks (Payton, 2007). The reliability and objectivity of digitising was assessed by calculating the within-digitiser (reliability) and between-digitiser (objectivity) absolute and relative RMSD between the variables calculated from the re-digitised coordinates. In order to calculate the relative RMSD, the range over which each variable changed when using the original digitisation was used as the dividing denominator. The identification of Tstart and MVstart was an important aspect of Theme 1 (Chapter 3). Therefore, reliability and objectivity was assessed by calculating the within and between digitiser RMS differences of the Tstart and MV start steps calculated from the re-digitised coordinates.

#### **Results and Discussion**

Regarding CM-h, an important variable for the detection of sprint phases in Chapter 3, the reliability analysis revealed that CM-h was consistent to within  $0.3 \pm 0.0\%$  of the participant's stature or  $3.0 \pm 0.0\%$  of the change in CM-h (Table A1). These differences were sufficiently low to allow the identification of step-to-step changes

in CM-h (Figure A1.1). Furthermore, the reliability analysis of the phases identified using CM-h revealed that the same steps was identified for  $T_{start}$  while MV<sub>start</sub> was detected to within 1 step (RMS difference of 0.8 steps).

Reliability and objectivity of shank, thigh and trunk angles revealed differences of between  $1 \pm 0^{\circ}$  to  $2 \pm 0^{\circ}$  for shank angles,  $2 \pm 0^{\circ}$  to  $3 \pm 0^{\circ}$  for thigh angles and  $2 \pm 0^{\circ}$  for trunk angles. It is important however that these RMSD are sufficiently small to be confident in the interpretation of the step-to-step patterns, which are discussed in Chapter 3. Figure A1.1 shows the unsmoothed step-to-step shank angle and trunk angles patterns for the re-digitised trial (both digitisers). These show that the RMSD were small enough to ensure that the step-to-step patterns were consistent between digitisations. When using touchdown shank angles, the same T<sub>start</sub> step was identified while using trunk angles MV<sub>start</sub> was identified to within 1 step (RMSD of 0.8 steps).

		Reliabi	lity	Objectiv	/ity		
Variable		RMSD	RMSD [%]	RMSD	RMSD [%]		
SV	[m⋅s⁻¹]	$0.03 \pm 0.01$	1 ± 0	$0.06 \pm 0.00$	1 ± 0		
SL	[m]	0.008 ± 0.001	1 ± 0	$0.033 \pm 0.002$	3 ± 0		
SF	[Hz]	$0.05 \pm 0.02$	4 ± 1	0.07 ± 0.01	5 ± 0		
$\theta_{trunk}$	[°]	2 ± 0	$4 \pm 0$	2 ± 0	4 ± 1		
$ heta_{ ext{thigh}}$	[°]	2 ± 0	2 ± 0	$3 \pm 0$	3 ± 0		
$ heta_{shank}$	[°]	1 ± 0	2 ± 0	2 ± 0	4 ± 0		
CM-h	[%]	$0.3 \pm 0.0$	3 ± 0	$0.5 \pm 0.0$	5 ± 0		
CD	[m]	$0.010 \pm 0.005$	4 ± 2	$0.035 \pm 0.003$	13 ± 1		
Events	[frames]	$0.4 \pm 0.2$	-	$0.6 \pm 0.0$	-		

**Table A1.1.** Reliability and objectivity of digitising. The values represent the absolute and relative differences between digitised trials of the same digitiser (reliability) and between digitised trials of different digitisers (objectivity).

-SV: step velocity; SL: step length; SF: step frequency;  $\theta_{trunk}$ : trunk angles;  $\theta_{thigh}$ : thigh angle;  $\theta_{shank}$ : shank angle; CD: contact distance

Other variables that are discussed in Chapter 3 include step velocity, step length, step frequency and contact distance. The analysis revealed RMSDs of  $0.03 \pm 0.01$  m·s<sup>-1</sup> (reliability) and  $0.06 \pm 0.00$  m·s<sup>-1</sup> (objectivity) for step velocity,  $0.008 \pm 0.001$  m (reliability) and  $0.033 \pm 0.002$  m (objectivity) for step length. The analysis also revealed with-digitiser differences of  $0.05 \pm 0.02$  Hz between-digitiser differences of  $0.07 \pm 0.01$  Hz for step frequency. The reliability differences were lower than the between trial standard deviations reported by previous studies investigating sprint

acceleration and maximal velocity phase. During initial acceleration standard deviation of  $0.07 \text{ m}\cdot\text{s}^{-1}$  were reported for velocity, 0.016 m for step length and 0.09 Hz for step frequency (Coh et al., 2006). During the maximal velocity phase, within participant SD ranged between  $0.16 \text{ m}\cdot\text{s}^{-1}$  to  $0.54 \text{ m}\cdot\text{s}^{-1}$  for step velocity, 0.04 to 0.06 m for step length and 0.08 to 0.27 Hz for step frequency (Bezodis, 2006). These reliability data show that uncertainties are small enough to allow the identification of between step and between trial differences.

The reliability and objectivity RMSD for contact distances were  $0.010 \pm 0.005$  m and  $0.035 \pm 0.003$  m. The reliability (within-digitiser) differences were similar to the reliability of 0.02 m reported by Churchill (2012) for touchdown distances. The larger objectivity differences for contact distances are likely due to the uncertainties associated with identifying the landmarks (i.e. centre of mass, MTP and toe), which are used to calculate the variables for touchdown and toe-off distance. The larger between-digitiser RMSDs for step length, step frequency and contact distances could be a result of the differences between the touchdown and toe-off events identified by the two digitisers. Due to the method used in Chapter 3 where touchdown and toe-off variables were approximated using the events from the panning camera, differences between the events will therefore have contributed to between-digitiser differences. The between-digitiser RMSD were  $0.6 \pm 0.0$  frames. The between-digitiser differences in the identification of touchdown and toe-off events revealed that the same event was identified 67% (34 events) of the time, that with 31% (16 events) of the events there was one frame difference (0.005 s) and with 2% (1 event) of the events there were two frames difference (0.010 s). The differences in events would have influenced the step time and the position of the CM at touchdown and therefore would have contributed to the between-digitiser differences in step length, step frequency and contact distance.

Overall, the reliability and objectivity analysis revealed that the uncertainties due to digitising were small enough to identify step-to-step changes between the initial acceleration and transition phases. Furthermore, the reliability and objectivity of the  $T_{start}$  and  $MV_{start}$  measures were within one step therefore providing confidence that these events are reliable enough to sub-divide the acceleration phase using either CM-h or shank and trunk angles.



**Figure A1.1.** Re-digitised step-to-step a) CM-h, b) shank angles, c) trunk angles and d) touchdown and toe-off distance profiles. Each figure contains the three digitisations by digitiser 1 (solid black lines) and digistiser 2 (dashed grey lines).

# **Appendix A2** - Individual T<sub>start</sub>, MV<sub>start</sub> and V<sub>max</sub> variables

Table A2.1. Participant mean (SD) as well as across participant mean (SD) and range of T<sub>start</sub> steps, CM-h, shank angles, step velocities and relative step velocities for each participant.

									Tstart								
						CM-h								Shank a	angles		
Participant	Day	S	step	Relative	e CM-h [%]	Veloc	ity (m⋅s⁻¹)	Relative \	/elocity (%)	S	tep	Degre	es [°]	Velocity	⁄ (m⋅s⁻¹)	Relative	Velocity (%)
		x	SD	x	SD	x	SD	x	SD	x	SD	x	SD	x	SD	x	SD
DO4	1	6.2	0.8	52	1	7.77	0.41	79	4.9	4.8	1.3	80	8	7.08	0.71	72.1	7.7
P01	2	4.0	0.7	51	0	6.71	0.44	67	3.7	4.6	1.1	78	3	7.07	0.67	70.7	6.5
DOO	1	3.8	0.8	50	1	6.61	0.55	62	4.9	4.0	0.7	73	4	6.73	0.42	63.2	3.9
P02	2	4.4	1.1	50	1	6.91	0.64	66	6.4	4.6	1.3	73	6	7.01	0.76	67.3	7.5
D03	1	3.6	0.5	49	1	6.55	0.45	62	4.3	5.0	1.4	77	12	7.29	0.72	69.0	6.9
F03	2	4.3	0.6	50	1	7.16	0.32	68	3.4	4.7	1.2	75	5	7.31	0.59	69.7	4.8
D04	1	4.2	0.8	52	1	5.96	0.50	67	5.2	5.0	0.0	85	2	6.38	0.07	71.8	0.5
F04	2	5.3	0.5	53	0	6.46	0.19	74	1.8	4.5	1.0	82	4	6.08	0.55	69.7	5.6
DOF	1	4.6	1.3	51	0	6.30	0.59	69	6.3	5.0	1.0	77	5	6.51	0.43	71.5	5.0
F00	2	5.8	1.0	52	1	6.78	0.38	75	4.5	5.0	0.8	74	6	6.44	0.36	71.4	4.5

									MV <sub>start</sub>								
						CM-h								Trunk a	ngles		
Participant	Day	Ste	∋p	Relative	e CM-h [%]	Velocity	⁄ (m⋅s⁻¹)	Relative \	/elocity (%)	St	ep	Degre	ees [°]	Velocity (m·s <sup>-1</sup> )		Relative	Velocity (%)
		x	SD	x	SD	x	SD	x	SD	x	SD	x	SD	x	SD	x	SD
DOA	1	15.4	1.1	56	0	9.56	0.18	97.3	0.9	16.6	1.1	82	3	9.63	0.16	98	1
PUI	2	15.2	1.8	56	1	9.67	0.18	96.7	1.7	15.6	0.9	83	3	9.72	0.14	97	1
D02	1	14.2	0.4	56	0	9.83	0.10	92.3	0.5	15.6	0.9	83	2	10.00	0.08	94	1
FUZ	2	13.4	0.9	55	1	9.70	0.14	93.1	1.9	14.8	1.8	80	2	9.80	0.26	94	3
P03	1	15.4	0.9	56	0	9.96	0.09	94.3	0.8	17.6	0.5	77	1	10.17	0.13	96	1
105	2	15.3	1.5	55	0	9.97	0.09	95.0	0.5	15.7	1.5	81	3	10.04	0.12	96	1
P04	1	14.4	1.9	54	0	8.48	0.19	95.4	2.1	14.6	0.5	82	1	8.51	0.07	96	1
104	2	14.5	1.3	55	0	8.23	0.05	94.4	2.1	15.8	2.2	81	3	8.32	0.11	95	3
POS	1	15.6	0.9	56	0	8.71	0.10	95.6	0.7	15.8	1.8	86	2	8.76	0.20	96	2
1.00	2	15.8	1.3	56	0	8.67	0.13	96.1	1.6	14.3	1.0	83	1	8.60	0.08	95	1

**Table A2.2.** Participant mean (SD) as well as across participant mean (SD) and range of MV<sub>start</sub> steps, CM-h, shank angles, step velocities and relative step velocities for each participant.

					CT≤FT										
Participant	Day	S	tep	Velocity	/ (m⋅s⁻¹)	Relative \	/elocity (%)	Step	)	Velocity	(m∙s⁻¹)	Trunk ang	gle (°)	) Relative (%	e CM-h ‰)
		x	SD	x	SD	x	SD	x	SD	x	SD	x	SD	x	SD
DO4	1	14.0	1.4	9.44	0.19	96.1	1.2	21.2	1.8	9.83	0.14	84	2	57	1
PUT	2	11.8	1.1	9.26	0.22	92.6	2.7	22.2	1.8	10.00	0.16	86	3	57	0
Doo	1	9.6	0.9	9.10	0.19	85.5	2.0	25.0	0.0	10.65	0.10	84	3	56	1
P02	2	10.6	1.1	9.21	0.16	88.4	1.6	22.8	1.5	10.42	0.08	82	1	56	1
D03	1	15.6	0.9	10.07	0.18	95.3	1.5	23.6	0.9	10.57	0.04	82	2	56	0
F03	2	12.0	0.0	9.62	0.05	91.7	0.9	23.3	1.2	10.49	0.12	84	2	55	0
D04	1	14.2	1.8	8.51	0.21	95.6	1.8	22.8	2.9	8.89	0.08	85	3	54	1
F 04	2	12.3	3.0	7.98	0.43	91.5	5.5	23.3	1.0	8.72	0.15	84	1	55	0
PO5	1	12.8	1.1	8.52	0.17	93.5	1.9	23.8	1.8	9.11	0.07	87	1	56	0
F 05	2	11.3	1.7	8.17	0.28	90.5	3.5	23.0	1.4	9.03	0.07	85	2	56	0

**Table A2.3.** Participant mean (SD) as well as across participant mean (SD) and range of CT $\leq$ FT and V<sub>max</sub> steps, absolute and relative step velocity at those steps and trunk angle at V<sub>max</sub>.

### Appendix A3 - CM angle

During the ground contact phase the CM angle has previously been linked to the anterior-posterior acceleration of the CM (di Prampero et al., 2005). In Chapter 3, the step-to-step progression of the components of CM angles, namely TD distance and toe-off distance and CM-h was investigated as these ultimately determine the orientation of the CM relative to the contact point. Similar to the finding of Theme 3 (Phase analysis), TD angles (Figure A3.1) showed a relatively steep between step increase during the initial acceleration phase when compared to the transition phase and maximal velocity phase. The toe-off angles increased at a similar rate during the initial acceleration phases. When comparing the between-step CM angle patterns to those of TD distances, toe-off distances and CM-h it is clear that TD distances and toe-off distances have the largest influence on changes in CM angle. This is due to the largest absolute changes in the horizontal variables compared to step-to-step changes in CM-h.



Figure A3.1. a) Touchdown CM angle and b) toe-off CM angle.

## Appendix A4 - Accuracy and reliability of joint kinematics and kinetics

Accuracies of reconstruction were determined as in Chapter 3. Six known points located along a pole were digitised. These digitised locations were then reconstructed and RMSD was calculated between the known and reconstructed position. The RMSD were mean across each separate data collection data and presented in figure A4.1.



Figure A4.1. Mean (-) and individual (•) horizontal and vertical reconstruction errors.

Reconstruction accuracies ranged from 0.001 m to 0.002 m horizontally and were 0.002 m vertically. These results show that data were reconstructed to comparable levels of accuracies between the different days on which data were collected. Challis and Kerwin (1996) showed that there is a degree of uncertainty associated with the calculation of joint kinetics. A main source of this uncertainty is related to inaccuracies associated with joint centre locations (Hunter et al., 2004c). Therefore, a reliability analysis was conducted to quantify the level of uncertainty associated with the digitising process. This was done by re-digitising one step three, nine and 19 trial three times on separate occasions. An RMSD and rel. RMSD was calculated between the original and re-digitised trials to quantify the inter-digitiser uncertainties associated with digitising.

 Table A4.1. Absolute and relative RMSD between re-digitised trials for step 3.

					0						
A	ngular	velocity*			Joint m	oment*			Joint F	ower*	
MTP	Ank	kle Kne	e Hip	MTP	Ankle	Knee	Hip	MTP	Ankle	Knee	Hip
56.3	30.6	23.5	19.5	0.000	0.001	0.007	0.029	0.046	0.183	0.159	0.631
4	5	10	11	1	1	8	5	4	5	12	5
54.1	28.7	30.7	36.9	0.000	0.001	0.009	0.029	0.035	0.231	0.176	0.692
4	5	13	21	1	1	10	5	3	7	14	6
	A MTP 56.3 4 54.1 4	Angular MTP Ani 56.3 30.6 4 5 54.1 28.7 4 5	Angular velocity*           MTP         Ankle         Knew           56.3         30.6         23.5         4           5         10         54.1         28.7         30.7           4         5         13         5         13	Angular velocity*MTPAnkleKneeHip56.330.623.519.545101154.128.730.736.9451321	Angular velocity*MTPAnkleKneeHipMTP56.330.623.519.50.000451011154.128.730.736.90.0004513211	Angular velocity*         Joint m           MTP         Ankle         Knee         Hip         MTP         Ankle           56.3         30.6         23.5         19.5         0.000         0.001           4         5         10         11         1         1           54.1         28.7         30.7         36.9         0.000         0.001           4         5         13         21         1         1	Angular velocity*         Joint moment*           MTP         Ankle         Knee         Hip         MTP         Ankle         Knee           56.3         30.6         23.5         19.5         0.000         0.001         0.007           4         5         10         11         1         1         8           54.1         28.7         30.7         36.9         0.000         0.001         0.009           4         5         13         21         1         1         10	Angular velocity*         Joint moment*           MTP         Ankle         Knee         Hip         MTP         Ankle         Knee         Hip           56.3         30.6         23.5         19.5         0.000         0.001         0.007         0.029           4         5         10         11         1         1         8         5           54.1         28.7         30.7         36.9         0.000         0.001         0.009         0.029           4         5         13         21         1         1         10         5	Angular velocity*         Joint moment*           MTP         Ankle         Knee         Hip         MTP         Ankle         Knee         Hip         MTP           56.3         30.6         23.5         19.5         0.000         0.001         0.007         0.029         0.046           4         5         10         11         1         8         5         4           54.1         28.7         30.7         36.9         0.000         0.001         0.009         0.029         0.035           4         5         13         21         1         10         5         3	Angular velocity*         Joint moment*         Joint F           MTP         Ankle         Knee         Hip         MTP         Ankle         Knee         Hip         MTP         Ankle         Source         Joint F           56.3         30.6         23.5         19.5         0.000         0.001         0.007         0.029         0.046         0.183           4         5         10         11         1         8         5         4         5           54.1         28.7         30.7         36.9         0.000         0.001         0.009         0.029         0.035         0.231           4         5         13         21         1         1         10         5         3         7	Angular velocity*         Joint moment*         Joint Power*           MTP         Ankle         Knee         Hip         MTP         Ankle         Knee         Hip         MTP         Ankle         Knee           56.3         30.6         23.5         19.5         0.000         0.001         0.007         0.029         0.046         0.183         0.159           4         5         10         11         1         8         5         4         5         12           54.1         28.7         30.7         36.9         0.000         0.001         0.009         0.029         0.035         0.231         0.176           4         5         13         21         1         1         10         5         3         7         14

\*normalised to dimensionless values.

 Table A4.2.
 Absolute and relative RMSD between re-digitised trials for step 9.

	1	Angular	velocity	/*		Joint m	oment*			Joint F	ower*	
	MTP	Ankle	Knee	Hip	MTP	Ankle	Knee	Hip	MTP	Ankle	Knee	Hip
$RMSD_{r1}$	82.7	42.4	27.0	30.7	0.001	0.002	0.007	0.039	0.054	0.410	0.231	1.053
$rel RMSD_1$	6	5	6	8	6	1	4	8	3	5	10	10
$RMSD_{r2}$	42.6	29.3	27.0	27.6	0.000	0.002	0.005	0.025	0.034	0.316	0.193	0.842
rel RMSD <sub>2</sub>	$5D_2$ 3 4 6 7			7	2	1	3	5	2	8		

\*normalised to dimensionless values.

 Table A4.3.
 Absolute and relative RMSD between re-digitised trials for step 19.

	ŀ	Angular v	elocity*			Joint m	noment'	•	Joint Power*					
	MTP	Ankle	Knee	Hip	MTP	Ankle	Knee	Hip	MTP	Ankle	Knee	Hip		
$RMSD_{r1}$	134.7	45.1	19.5	18.2	0.000	0.008	0.009	0.033	0.149	0.843	0.130	1.110		
$rel RMSD_1$	8	4	6	8	2	4	4	6	8	5	7	8		
$RMSD_{r2}$	103.8	32.2	20.8	20.1	0.001	0.003	0.006	0.032	0.136	0.547	0.117	1.045		
$rel RMSD_2$	6	3	6	9	3	1	3	6	7	4	6	7		

\*normalised to dimensionless values.

The results of this reliability analysis reveals a level of uncertainty associated with the digitisation process that is largest for the joint variables. At the hip, uncertainties in the calculated joint moments ranges between 0.025 - 0.039 (5 - 8% of the range) while uncertainties in hip joint powers ranged between 0.631 - 1.110 (5 - 10% of the range). This can in part be influenced by the propagation of errors as joint kinetics higher up the chain are calculated, as well as the difficulty in identifying the hip joint centre when digitising. The purpose of Chapter 4 is to identify changes between steps three, nine and 19. Although some of these uncertainties are quite large (especially the hip powers), figure A4.2 shows that these uncertainties are still low enough to confidently identify differences between steps three, nine and 19.



Figure A4.2. Continuous time-history joint angle, joint angular velocity, joint moment and joint power data obtained from the re-digitised step three (black), nine (blue) and 19 (red) trials.

## Appendix A5 - Components of IAA

## Matrix A

The matrix A (Figure A5.1 & Figure A5.2) is a  $27 \times 27$  (rows  $\times$  columns) matrix and contains the Newton-Euler and constraint equations for the 5 segment system. Per segment (n) there are three components describing linear acceleration (Newton equations) and three components describing the angular accelerations (Euler equations). This provides a total of 6n or 30 components. Because the forces acting on each contact point are partly formed by connections (i.e. inter segmental forces) and these forces components (three per contact point) are unknown. The system is overdetermined and therefore constraint equations describing these intersegmental force components are needed. At least as many constraint equations as contact point are needed. With each constraint describing the three force components, at least one equation is needed per contact point. For further information, see Hof and Otten (2005) and Otten (2003).

Figure A5.1. Components of matrix A. Matrix A is a square matrix with 27 rows and 27 columns.

Rows 1 to 10 of matrix A represent linear equations of motion (Equation A5.1) for the 5 segments.

$$F_i - F_{i+1} + m_i g = m_i a_i$$
 [Equation A5.1]

where segment masses and gravity are known and the force and accelerations are unknown. Equation A5.1 can be rearranged to isolate the unknown components on the left-had side:

$$F_i - F_{i+1} - m_i a_i = -m_i g \qquad [Equation A5.2]$$

Rows 11 to 18 of matrix A represents the constraint equations (Equation A5.3) coupling the segments at the MTP, ankle, knee and hip joints.

$$\vec{a}_{ji} = \vec{a}_i + \left( \ddot{\theta}_i \times \vec{r}_{ji} \right) - \left( \dot{\theta}_i^2 \times \vec{r}_{ji} \right)$$
[Equation A5.3]

Equation A5.3 represents the accelerations at the j<sup>th</sup> joint ( $\vec{a}_{ji}$ ) of the i<sup>th</sup> segment.  $\vec{a}_i$  is the unknown acceleration of the centre off masses on the i<sup>th</sup> segments;  $\dot{\theta}_i$  is the unknown angular acceleration of the i<sup>th</sup> segments;  $\dot{\theta}_i^2$  is the known angular velocities of the i<sup>th</sup> segment. The distances between the centre of mass of the segment and the proximal (p) or distal (d) joint is represented by the known radial arm  $\vec{r}_{ji}$ . Equation A5.4 and Equation A5.5 describe the coupling of the joints ensuring matched accelerations of the joints between two adjoining segments (Hof & Otten, 2005; Heitmann, Ferns & Breakspear, 2012).

$$\vec{a}_{pi} = \vec{a}_{d(i+1)}$$
[Equation A5.4]  
$$\vec{a}_{pi} + (\ddot{\theta}_i \times \vec{r}_{pi}) - (\dot{\theta}_i^2 \times \vec{r}_{pi}) = \vec{a}_{d(i+1)} + (\ddot{\theta}_{d(i+1)} \times \vec{r}_{d(i+1)}) - (\dot{\theta}_{d(i+1)}^2 \times \vec{r}_{d(i+1)})$$
[Equation A5.5]

Equation A5.5 can be rearranged to isolate the unknown linear and angular acceleration terms:

$$\vec{a}_{2i} - \vec{a}_{(i+1)} + (\ddot{\theta}_i \times \vec{r}_{pi}) - (\ddot{\theta}_{(i+1)} \times \vec{r}_{d(i+1)}) = -(\dot{\theta}_{(i+1)}^2 \times \vec{r}_{d(i+1)}) + (\dot{\theta}_i^2 \times \vec{r}_{pi})$$
[Equation A5.6]

Rows 19 to 23 of matrix A represent the equations of angular motion (Equation A5.7).

$$(F_{di} \times r_{di}) - (F_{pi} \times r_{pi}) + M_{di} - M_{pi} = I_i \times \ddot{\theta}_i$$
 [Equation A5.7]

where  $F_{di}$  and  $F_{pi}$  are the unknown distal and proximal forces;  $M_{di}$  and  $M_{pi}$  are the known distal and proximal joint moments and  $\ddot{\theta}_i$  is the unknown angular acceleration of the segment. Equation A5.7 can be re-arranged to isolate the unknown components:

$$-(F_{di} \times r_{di}) + (F_{pi} \times r_{pi}) - I_i \times \ddot{\theta}_i = -M_{di} + M_{pi}$$
 [Equation A5.8]

Finally, Rows 24 to 27 of matrix A represents the contact constraint equations and describe the force components at contact point between the foot and the ground (Equation A5.9). The required components to describe these forces and accelerations are put into rows and columns 24 to 27 of Matrix A. The contact

constraint equations ensure that the contact points with the ground have zero acceleration meaning.

$$\vec{a}_{p1} = \vec{a}_{d0} = \mathbf{0}$$
 [Equation A5.9]

where  $\vec{a}_{p1}$  and  $\vec{a}_{d0}$  are the accelerations at the contact point. Again, Equation A5.9 can be re-arranged to isolate the unknown components. In this case the components relating to the acceleration of the ground are zero.

$$\vec{a}_1 + (\ddot{\theta}_1 \times \vec{r}_1) - (\dot{\theta}_1^2 \times \vec{r}_1) = \mathbf{0}$$
[Equation A5.10]

where  $\vec{a}_1 + (\ddot{\theta}_1 \times \vec{r}_1)$  represent the known accelerations (acy &acz) at the contact point between the segment and the ground (Figure A5.3).

			M	TP	An	ikle	Kn	iee	н	ip	fFo	oot	rF	oot	Sha	ank	Th	igh	H/	AT	fFoot	rFoot	Shank	Thigh	HAT	Fe	Fe	Fe	Fe
			Fx	Fy	Fx	Fy	Fx	Fy	Fx	Fy	ax	ay	ах	ay	ах	ay	ах	ay	ах	ay	$\ddot{ heta}$	$\ddot{ heta}$	$\ddot{ heta}$	$\ddot{ heta}$	Ö	х	У	х	У
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
fFoot	х	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
	у	2	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
rFoot	X	3	1	0	-1	0	0	0	0	0	0	0	-m2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
	у	4	0	1	0	-1	0	0	0	0	0	0	0	-m2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Shank	х	5	0	0	1	0	-1	0	0	0	0	0	0	0	-m3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	у	6	0	0	0	1	0	-1	0	0	0	0	0	0	0	-m3	0	0	0	0	0	0	0	0	0	0	0	0	0
Thigh	Х	7	0	0	0	0	1	0	-1	0	0	0	0	0	0	0	-m4	0	0	0	0	0	0	0	0	0	0	0	0
	у	8	0	0	0	0	0	1	0	-1	0	0	0	0	0	0	0	-m4	0	0	0	0	0	0	0	0	0	0	0
HAT	Х	9	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	-m5	0	0	0	0	0	0	0	0	0	0
	у	10	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	-m5	0	0	0	0	0	0	0	0	0
MTP	х	11	0	0	0	0	0	0	0	0	1	0	-1	0	0	0	0	0	0	0	<b>-ľ</b> 12y	ľ21y	0	0	0	0	0	0	0
	у	12	0	0	0	0	0	0	0	0	0	1	0	7	0	0	0	0	0	0	ľ 12x	- ľ 21x	0	0	0	0	0	0	0
Ankle	х	13	0	0	0	0	0	0	0	0	0	0	1	0	-1	0	0	0	0	0	0	-r <sub>22y</sub>	r <sub>31y</sub>	0	0	0	0	0	0
	у	14	0	0	0	0	0	0	0	0	0	0	0	1	0	7	0	0	0	0	0	ľ 22x	- ľ 31x	0	0	0	0	0	0
Knee	х	15	0	0	0	0	0	0	0	0	0	0	0	0	1	0	-1	0	0	0	0	0	-r <sub>32y</sub>	<b>r</b> <sub>41y</sub>	0	0	0	0	0
	у	16	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	-1	0	0	0	0	r <sub>32x</sub>	- r <sub>41x</sub>	0	0	0	0	0
Hip	х	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	-1	0	0	0	0	- <b>r</b> <sub>42y</sub>	<b>r</b> <sub>51y</sub>	0	0	0	0
	у	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	-1	0	0	0	ľ 42x	- ľ 51x	0	0	0	0
fFoot		19	ľ1py	<b>-ľ</b> 1px	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<b>-ľ</b> e1y	ľe1x	ľe2y	-ľe2x
rFoot		20	<b>-ľ</b> 2dy	ľ2dx	ľ 2py	- ľ 2px	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<b>-1</b> 2	0	0	0	<b>-ľ</b> e1y	le1x	0	0
Shank		21	0	0	<b>-ľ</b> 3dy	ľ 3dx	r <sub>3py</sub>	- ľ 3px	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<b>-I</b> 3	0	0	0	0	0	0
Thigh		22	0	0	0	0	<b>-ľ</b> 4dy	ľ4dx	۲4py	<b>-ľ</b> 4px	0	0	0	0	0	0	0	0	0	0	0	0	0	-14	0	0	0	0	0
HAT		23	0	0	0	0	0	0	<b>-ľ</b> 5dy	ľ 5dx	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<b>-1</b> 5	0	0	0	0
CoP		24	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	-r <sub>e1y</sub>	-r <sub>e1y</sub>	0	0	0	0	0	0	0
CoP		25	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	r <sub>e1x</sub>	r <sub>e1x</sub>	0	0	0	0	0	0	0
CoP		26	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	- <b>r</b> e2y	0	0	0	0	0	0	0	0
CoP		27	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	Logy	0	0	0	0	0	0	0	0

**Figure A5.2**. Full matrix A used for the IAA adapted from (Hof & Otten, 2005). Rows 1 to 10 contain the coefficients for the equations of linear acceleration (equations 5.10). Rows 11 to 18 contain the coefficients for the constraint equations (equations 5.13). Rows 19 to 20 are the coefficients for the equations of angular acceleration (equation 5.17). Rows 24 to 27 contain the coefficients for the constraint equations with the ground. It is important to remind the reader at this point that two contact models were used. At the beginning and end of ground contact when the one-point contact model applied, contact was modelled either between the fore foot (yellow shaded) or rear foot (red shading). This was dependent on the location of the COP relative to the MTP joint. For example, when the COP was behind the MTP joint, all the inputs in red text were removed from the matrix and replaced by zeros. During the stationary fore foot phase of ground contact, the two-point contact model was used (see 5.2.1.2 Contact model). Rows 24 to 27 and columns 24 to 27, were filled cording to the red text. In this case contact coefficients describing contact at the projected MTP location are added to rows and columns 24 to 25, while the coefficients describing contact at the projected TOE location are added to rows and columns 26 to 27.

### Vector c

Vector c is a 27 × 1 column vector containing known variables isolated on the right side of equations A5.2, A5.6, A5.8, A5.10 (Figure A5.3). Rows 1 – 10 include the external forces acting on segments 1 to 5. This was either gravity ( $m_ig$ ) or the force exerted by the contralateral leg on the trunk segment ( $F_{5x}$ ,  $F_{5y}$ ). Rows 11 to 18 include the variables of the centripetal accelerations of the MTP, ankle, knee and hip joints. These use the angu7lar velocity of the segments ( $\dot{\theta}_i^2$ ) as inputs. Likewise, rows 24 to 27 include the centripetal accelerations of the most distal segment. The variables  $ac_x$  and  $ac_y$  (Equation A5.10) are the known accelerations at the contact point between the foot and the ground (Otten, 2003). For further information see Hof and Otten (2005) and Otten (2003).



**Figure A5.3**. Variables contained within the column vector c adapted from (Hof & Otten, 2003). When the COP was behind the MTP joint, all the inputs in red were removed from the matrix and replaced by zeros. Variables in red are replaced by zeros when the COP was behind the MTP joint.

# Vector x

This is a 1 × 27 column vector of unknowns. From top to bottom, this vector consists of: the y and z components of the intersegmental forces at the MTP, ankle, knee and hip (rows 1 -10); the y and z components of the linear accelerations of the fore foot, rear foot, shank, thigh and HAT segments (rows 11 - 18); the angular accelerations of the fore foot, rear foot, shank, thigh and HAT segments (rows 19 - 24) and the y and z components of the ground reaction forces (rows 25 - 27). For further information see Hof and Otten (2005) and Otten (2003).

#### **Appendix A6** - Foot-floor models in maximal sprinting

**INTRODUCTION:** The results of an IAA not only depends on the characteristics of the model (Chen, 2005) but also model used to describe ground contact (Dorn et al., 2012). In the literature the foot-floor interaction has previously been modelled at a single point (i.e. the instantaneous COP; Kepple et al., 1997; Hof & Otten, 2005; Cabral et al., 2013; Koike & Nagai, 2016; Koike et al., 2017) or across multiple-points (e.g. Lin et al., 2011; Dorn et al., 2012; Koike, Ishikawa & Ae, 2010). Furthermore, IAA studies in sprinting have generally modelled the foot as a single segment (Cabral et al., 2013; Koike & Nagai, 2016). However, the foot is a complex multi-segment structure (Hamner, Seth, Steele & Delp, 2013) with the MTP joint showing a relatively large range of motion during the stance phases in sprinting (Bezodis et al., 2012). The aim of this study was therefore to compare the results of an IAA when using a single-segment or two-segment foot model. Furthermore, a second aim was to compare IAA results when using a single point versus multi-point model to define the foot-floor contact model when using a two-segment foot. The purpose of this will be to inform future work using IAA in Chapter 5. For a contact model to be identified as suitable, two conditions need to be met. Firstly, the model needs to provide accurate results when compared to the measured CM accelerations. Secondly, the contributions by the individual inputs (e.g. joint moments) need to be realistic. This means that the contributions to CM acceleration by the individual inputs need to provide a realistic and meaningful interpretation of the results.

**METHODS:** Sagittal plane kinematics (200 Hz video) and three dimensional ground reaction forces (1000 Hz) were collected from 13 participants performing acceleration from blocks. Data was collected from steps three, nine and 19 and the best trial from each step was selected for further analysis. After extracting the videos using Dartfish Team Pro 6.0 (Dartfish), converting them to .avi format and de-interlaced in VLC 2.1.3 (VideoLan, France), they were digitised in Matlab (The MathWorks Inc., USA, version R2014a) using an 18 point model. The digitised coordinates were then reconstructed using a nine-parameter 2D-DLT with lens correction (Walton, 1981). Kinematic data were filtered with a 4<sup>th</sup> order low pass Butterworth filter with a 26 Hz cut-off frequency. The body was modelled using five segments; fore foot, rear foot, shank, thigh and head, arms and trunk (HAT). Data
from de Leva (1996) were used to calculate the inertia data for all the segments except the foot. For the foot segments, data used by Bezodis et al. (2014) was used with the mass of the sprint shoe added. Linear and angular segment velocities and accelerations were calculated using a three point central differences method (Miller & Nelson, 1976). Ground contact was identified using a 10 N threshold before down sampling to 200 Hz and filtered with a 4<sup>th</sup> order low pass Butterworth filter with a 26 Hz cut-off frequency. Joint moments were calculated according to Winter (2009) where the fore foot segment and MTP were included in the calculation when the COP was in front of the MTP joint (Stefanyshyn & Nigg, 1997). An IAA was performed according to the methods proposed by Hof & Otten (2005). Ground contact was modelled using three methods (Figure A6.1). The first method involved a single segment foot where ground contact was modelled as a joint between the foot and the COP (Figure A6.1a). The second involved a two segment foot with a joint being defined between the COP and CM of the rear foot when the COP was located behind the MTP joint and the between the COP and the MTP joint when the COP was located in front of the MTP (Figure A6.1b). The third foot model involved a mix approach. At the start and end when the MTP and Toe were above a vertical threshold the foot model two was used. When either the MTP, toe or both where below the vertical threshold, then a two point contact model was used. In this case, contact was defined at the locations of the MTP joint and the toe (Figure A6.1c; also see 5.2.1.2 Contact model).



**Figure A6.1**. Three ground contact models used in the current study. The contact model in a) involves a 1 segment foot where contact is modelled between the foot and the ground via the COP (1SegFoot\_ COP). The contact model in b) involves a two-segment foot where contact with the ground is modelled between the COP and the distal segment (2SegFoot\_ COP). The contact model in c) involves a two-segment foot and used the COP at the beginning and end of ground contact and the MTP joint and toe when the forefoot was stationary on the ground (2SegFoot\_TwoPoint).

The accuracy of the analysis was determined by calculating the RMSD between the measured CM acceleration and the summed contributions to CM acceleration by all inputs (i.e. joint moments, centripetal accelerations, gravity). An RMSD of zero meant that the summed contributions and the measured GRF matched perfectly. A relative RMSD was then calculated as the RMSD relative to the horizontal, vertical and resultant GRF excursion. The relative RMSD was calculated for each participant separately before calculating an ensemble mean RMSD across all participants. The contributions by the individual joint moments were averaged across the stance phases of steps three, nine and 19. An ensemble mean for each step was then calculated across all participants.

**RESULTS and DISCUSSION:** The aim of this study was to compare the results of an IAA when using single-segment or two-segment foot model and a single point or multi-point foot-floor contact definition. The will help to inform future work using IAA to investigate the contributions to performance in sprinting. The first requirement of the model is that it needs to provide accurate data. The models need to provide accurate results. Figure A6.2 shows the absolute RMSD between the measured (using GRF data) CM accelerations and the total induced CM accelerations. Accuracy was slightly better for the models that used the 2\_segment foot. The relative RMSD for the three contact models ranged from 1% - 5% (1SegFoot\_CoP; 2% - 5%; 2SegFoot\_CoP: 1% - 4%; 2SegFoot\_TwoPoint: 1% - 3%).



**Figure A6.2.** The relative RMSD between the measured anterior-posterior (), vertical () and resultant () accelerations between the calculated and the total calculated induced CM accelerations for steps three (left), nine (middle) and 19 (right). The three foot-ground models are a) 1segment foot model connected to the floor at the COP, b) 2segment foot model connected to the floor at the COP, c) 2segment foot multi-contact point model.

Dorn et al. (2012) compared the effect of various contact models on the results of an IAA in walking and running. They reported that medio-lateral IAA results were more sensitive to the contact models than the vertical and anterior-posterior induced accelerations (Dorn et al., 2012). In their study the hinge and multi-point joints were comparable to the contact models of the current study and while both showed accuracies below 10% of the measured data, the multi-point model showed the greater accuracy in the running condition with relative RMSD of ~5% (Dorn et al., 2011). Furthermore, the results from the current study show a slightly larger relative RMSD at the higher velocities. A similar trend has been shown by Dorn et al. (2011), however not as pronounced as the difference between walking and running. These increasing RMSDs resulted from increased errors with approximating the GRFs at the beginning and end of stance when external forces are lower. This may be linked to the fluctuations of the COP that can be observed during low force conditions (Koike et al., 2017).

The second condition that needs to be satisfied is the validity of the results regarding the individual contributions. The foot complex (FC; ankle + MTP) provided the largest contribution to CM acceleration, of which the ankle joint made up the largest share (Table A6.1).

	0							
	Input		1segFoo	ot_COP	2segFo	ot_COP	2SegFoot	TwoPoint
			CM_acc y	CM_acc z	CM_acc y	CM_acc z	CM_acc y	CM_acc z
	MTP	[m·s <sup>-2</sup> ]	-	-	1.63 ± 4.22	7.52 ± 5.87	-1.29 ± 0.56	-0.37± 0.49
ю	Ankle	[m·s <sup>-2</sup> ]	6.25 ± 0.87	12.49 ± 1.54	4.10 ± 4.26	5.50 ± 5.78	7.53 ± 1.10	12.80 ± 1.48
tep	FC*	[m⋅s <sup>-2</sup> ]	6.25 ± 0.87	12.49 ± 1.54	5.73 ± 0.84	13.03 ± 1.37	6.24 ± 0.87	12.43 ± 1.49
S	Knee	[m·s <sup>-2</sup> ]	$-0.99 \pm 0.43$	1.22 ± 0.73	-0.62 ± 0.32	$0.83 \pm 0.48$	-1.00 ± 0.39	1.22 ± 0.67
	Hip	[m·s <sup>-2</sup> ]	-0.14 ± 0.10	-0.07 ± 0.26	-0.09 ± 0.10	0.12 ± 0.17	-0.15 ± 0.11	0.09 ± 0.22
	MTP	[m·s <sup>-2</sup> ]	-	-	$0.95 \pm 3.99$	8.29 ± 4.74	-1.29 ± 0.52	-0.10 ± 0.49
6	Ankle	[m·s <sup>-2</sup> ]	4.67 ± 0.88	15.94 ± 1.86	3.08 ± 3.85	8.22 ± 4.74	5.92 ± 1.15	15.94 ± 1.88
tep	FC*	[m·s <sup>-2</sup> ]	4.67 ± 0.88	15.94 ± 1.86	$4.03 \pm 0.66$	16.51 ± 1.82	4.63 ± 0.84	15.84 ± 1.86
S	Knee	[m·s <sup>-2</sup> ]	-1.42 ± 0.65	1.25 ± 0.81	-0.92 ± 0.47	0.88 ± 0.44	-1.44 ± 0.60	1.42 ± 0.81
	Hip	[m·s <sup>-2</sup> ]	-0.36 ± 0.10	0.08 ± 0.22	-0.31 ± 0.07	0.28 ± 0.16	-0.36 ± 0.09	0.26 ± 0.20
	MTP	[m⋅s <sup>-2</sup> ]	-	-	-0.53 ± 4.61	8.16 ± 5.59	-1.14 ± 0.62	-0.29 ± 0.65
6	Ankle	[m·s <sup>-2</sup> ]	3.37 ± 1.11	19.09 ± 2.90	$3.45 \pm 4.54$	11.32 ± 4.62	4.51 ± 1.06	19.29 ± 2.96
ep 1	FC*	[m·s <sup>-2</sup> ]	3.37 ± 1.11	19.09 ± 2.90	2.92 ± 1.01	19.47 ± 2.89	3.37 ± 1.11	19.00 ± 2.83
Š	Knee	[m·s <sup>-2</sup> ]	-1.48 ± 1.12	1.23 ± 1.10	-1.14 ± 0.89	1.00 ± 0.91	-1.54 ± 1.09	1.42 ± 1.10
	Hip	[m⋅s <sup>-2</sup> ]	$-0.39 \pm 0.17$	$0.10 \pm 0.24$	-0.36 ± 0.15	0.31 ± 0.16	-0.39 ± 0.18	$0.26 \pm 0.20$

**Table A6.1.** Average ± SD MTP, ankle, FC, knee and hip moment contributions to CM acceleration using the three foot-ground models during steps 3, 9 and 19.

CM\_acc y: Horizontal CM acceleration; CM\_acc z: Vertical CM acceleration; \*FC: Foot complex (MTP + Ankle moment contribution)

However, while the contributions by the FC were similar between the three contact models, the contributions by the ankle and MTP moments differed between the three

contact models (Table A6.1). Since the fore foot motion is largely restricted by the ground during the majority of stance, the two-point contact model might be a more realistic representation. Furthermore, foot pressure mapping data from sprinting shows that contact occurs across the metatarsals and toes (Smith, 2012). This further suggests that modelling contact using constraints at the toe and MTP is more realistic than just using a single point. This definition of modelling contact at the horizontal locations of the MTP and toe has previously been successfully used by Bezodis et al. (2015) in a simulation study of the first stance in sprinting. Using the COP in the definition of ground contact could lead to errors in the calculation of an IAA. This is due to the relatively large fluctuations in the anterior-posterior location of the COP during ground contact, while the position of the foot remains relatively unchanged (Koike et al., 2017). This will have the effect of creating large fluctuations in the length of the moment arm between the COP and CM of either the fore or rear foot, leading to an overestimation of the accelerations (Koike et al., 2017). Koike et al. (2017) therefore suggested using contact points that are fixed to the base of the foot.

While the 2SegFoot\_CoP contact model might suggest that the MTP shows large horizontal and vertical contributions to CM accelerations (Table A6.1), the two-point model suggests that the MTP moment induces small negative accelerations on the CM while the ankle moment contributed large upward and forward CM accelerations. This is in line with the results by Koike, Ishikawa and Ae (2010). In the study by Koike et al. (2010), relatively small backward and downward accelerations induced by the MTP moment were reported, while the ankle moment was the largest contributor to forward and upward CM acceleration. These results can be understood in terms of the mechanics of linked segments. With the fore foot constrained, an MTP plantar flexor moment would induce an anti-clockwise (direction of movement viewed from left to right) motion on the rear foot segment. This would result in a backward and downward motion of the rear foot, shank, thigh and upper body segments. Overall, the multi-point contact model is therefore more suitable, especially if a two-segment foot is used.

## Appendix A7- Induced segment accelerations at the peak braking, vertical and propulsive force events

		Tour -			angalai	maaoo	ou oogii		oororaa	ono at	and po		aang io	100 0				P.								
	Joint M	loment						Linear induced accelerations [m·s <sup>-2</sup> ]							Ang	ular indu	iced acc	eleration	s [rad·s <sup>-?</sup>	<sup>2</sup> ]						
	[norma	alised]		Rea	r Foot			Sha	ank			Th	igh			HA	٩T		Rear	Foot	Sha	ank	Thi	gh	HA	Τ
			Horiz	ontal	Vert	tical	Horiz	ontal	Ver	tical	Horiz	ontal	Verti	ical	Horizo	ontal	Ver	tical								
	Mean	± SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD
MTP	0.00	0.01	-1.46	2.92	-0.98	1.63	-2.62	5.03	-1.76	3.01	-0.93	1.78	-0.81	1.44	0.12	0.21	-0.04	0.07	20.09	36.01	0.05	1.47	-7.43	13.93	0.67	1.21
Ankle	0.02	0.02	10.68	8.22	9.41	7.37	18.51	13.93	16.94	13.06	5.06	3.78	8.77	6.61	-1.40	1.06	1.17	1.02	-158.50	118.01	0.79	9.44	56.36	42.81	-10.89	8.33
Knee	0.00	0.02	-0.51	4.14	-0.48	3.65	-0.94	9.63	-0.68	5.35	-0.44	4.84	-0.22	0.70	0.10	0.72	0.22	1.89	8.22	64.37	-0.08	12.21	-2.61	28.65	0.35	5.51
Hip	0.08	0.04	-17.67	8.66	-12.40	6.78	-27.03	11.81	-24.24	11.34	-4.01	2.86	-11.62	5.46	2.88	1.41	5.43	2.41	240.12	105.35	-12.10	22.32	-91.70	39.75	37.23	15.14

#### Table A7.1. Mean ±SD linear and angular induced segment accelerations at the peak braking force event of the third step.

#### Table A7.2. Mean ±SD linear and angular induced segment accelerations at the peak braking force event of the ninth step.

	Joint N	loment						Linea	r induce	d accele	erations	[m·s <sup>-2</sup> ]								Ang	ular indu	iced acc	elerations	s [rad∙s <sup>∹</sup>	<sup>2</sup> ]	
	[norma	alised]		Rear	Foot			Sha	ank			Tł	nigh			Н	AT		Rear	Foot	Sha	ank	Thig	gh	HA	۸T
			Horiz	ontal	Vert	ical	Horizo	ontal	Vert	ical	Horiz	ontal	Vert	ical	Horiz	ontal	Vert	tical								
	Mean	± SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD
MTP	0.00	0.00	-0.21	0.74	0.02	0.08	-0.06	0.21	0.04	0.15	0.01	0.05	0.01	0.04	0.00	0.00	0.00	0.00	-0.67	2.41	-0.52	1.89	0.10	0.38	-0.01	0.02
Ankle	0.05	0.03	20.99	6.50	18.76	8.16	31.32	11.31	38.42	16.03	2.88	2.54	22.21	9.25	-4.11	1.72	5.70	2.88	-340.00	124.77	9.09	18.70	114.73	49.20	-40.45	16.97
Knee	-0.02	0.02	3.77	3.35	3.66	4.19	12.00	12.09	7.20	8.71	6.81	7.16	0.93	2.12	-0.72	0.85	-2.43	2.19	-69.01	74.09	-25.54	30.23	41.92	44.14	3.77	3.13
Hip	0.17	0.06	-32.42	11.98	-28.60	10.68	-56.58	18.82	-56.80	20.12	-6.78	5.14	-22.94	9.05	4.53	1.95	12.14	4.10	508.92	164.44	22.98	43.03	-231.46	79.30	93.46	31.57

#### Table A7.3. Mean ±SD linear and angular induced segment accelerations at the peak braking force event of the 19<sup>th</sup> step.

	Joint M	loment						Linear	induced	d accele	erations	[m·s <sup>-2</sup> ]								Ang	ular indu	iced acc	eleration	s [rad·s <sup>-2</sup>	<sup>2</sup> ]	
	[norma	alised]		Rea	r Foot			Sha	ınk			Thi	gh			HA	λT		Rear	Foot	Sha	ank	Thi	gh	HA	٩T
			Horiz	ontal	Vert	ical	Horiz	ontal	Ver	ical	Horiz	ontal	Verti	cal	Horiz	ontal	Ver	tical								
	Mean	± SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD
MTP	0.00	0.00	-0.10	0.31	-0.14	0.49	-0.24	0.86	-0.24	0.88	-0.05	0.18	-0.16	0.60	0.03	0.10	-0.08	0.28	1.77	6.44	0.33	1.32	-1.00	3.63	0.34	1.22
Ankle	0.08	0.03	24.18	8.83	22.69	7.39	34.94	16.79	45.68	15.73	-2.10	4.91	28.15	8.44	-6.49	2.19	13.44	4.91	-412.85	170.37	19.47	20.61	135.02	57.17	-58.78	16.32
Knee	-0.01	0.03	1.01	5.17	1.28	5.19	6.57	21.18	2.96	10.46	3.93	11.46	0.73	2.10	-0.46	1.29	-1.10	4.10	-22.09	88.19	-21.27	58.29	26.56	80.66	-0.63	4.08
Hip	0.14	0.05	-24.72	11.19	-23.11	9.26	-53.49	18.43	-46.25	17.19	-5.50	4.13	-16.11	6.43	3.60	1.51	9.71	3.65	410.74	162.70	60.37	43.83	-240.74	85.46	102.28	41.85

- Negative value represents a backward or downward linear and clockwise angular induced acceleration.

Table A7.4. Mean ±SD linear and angular induced segment accelerations at the peak vertical force event of the third step.

	Joint I	Moment						Linear	induced	d accel	erations	[m·s <sup>-2</sup> ]								Ang	jular indu	uced acc	elerations	s [rad∙s <sup>-2</sup>	<sup>2</sup> ]	
	[norm	nalised]		Rear	Foot			Sha	nk			Tł	nigh			Н	AT		Rear	Foot	Sha	ank	Thi	gh	HA	۸T
			Horiz	ontal	Vert	ical	Horiz	ontal	Ver	tical	Horiz	ontal	Vert	ical	Horiz	ontal	Ver	tical								
	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD
MTP	0.02	0.01	-7.89	5.05	-6.15	3.61	-17.79	10.96	-7.07	4.01	-7.22	4.47	-3.09	1.61	0.47	0.30	-0.91	0.53	122.03	74.26	22.48	13.04	-50.36	29.60	6.81	3.89
Ankle	0.18	0.02	59.93	9.39	49.51	9.95	126.58	17.21	67.67	13.37	43.18	8.81	44.12	7.17	-2.93	1.22	16.14	2.42	-940.23	119.28	-121.31	30.35	371.21	44.43	-96.95	17.73
Knee	0.08	0.02	-20.94	5.72	-17.40	5.73	-53.92	12.53	-13.70	6.56	-23.06	4.78	3.40	1.28	6.00	1.35	5.40	1.59	328.15	84.39	102.42	24.11	-165.23	38.62	0.49	5.46
Hip	0.10	0.04	-21.08	7.25	-17.58	7.33	-46.54	16.08	-22.16	9.62	-10.33	4.88	-12.14	4.94	6.00	2.26	5.27	2.01	334.49	120.01	54.53	21.02	-163.34	53.46	63.40	20.74

Table A7.5. Mean ±SD linear and angular induced segment accelerations at the peak vertical force event of the ninth step.

	Joint I [norm	Moment nalised]						Linea	r induce	d accel	erations	[m⋅s <sup>-2</sup> ]							Ang	ular indu	ced acc	elerations	s [rad∙s⁻²	]	
				Rea	r Foot			Sh	ank			Thig	h		HA	λT		Rear	Foot	Sha	nk	Thi	gh	HA	Т
			Horiz	ontal	Vert	ical	Horizo	ontal	Vert	ical	Horiz	ontal	Vertical	Horizo	ontal	Vert	ical								
	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean ±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD
MTP	0.01	0.01	-2.14	2.03	-2.75	2.44	-5.65	5.23	-3.77	3.31	-2.31	2.14	-1.58 1.37	0.24	0.21	-0.37	0.36	42.56	38.27	9.36	8.51	-19.06	17.33	2.57	2.37
Ankle	0.20	0.03	52.01	8.73	61.44	10.75	115.05	16.50	100.29	15.00	31.44	10.32	57.58 6.76	-7.81	1.93	20.81	4.25	-1030.94	147.77	-123.89	47.88	406.48	57.82	-111.38	18.05
Knee	0.10	0.03	-20.01	7.17	-24.55	10.15	-61.17	21.51	-30.07	11.32	-28.72	10.29	-2.77 1.96	5.49	2.37	8.35	2.68	398.68	145.32	129.44	45.84	-210.90	76.48	6.13	7.67
Hip	0.11	0.06	-18.53	10.46	-21.11	9.85	-43.70	20.94	-33.41	18.30	-6.33	5.58	-13.41 7.04	4.43	2.19	6.75	3.65	359.68	185.86	58.95	33.01	-183.88	88.70	76.11	38.35

### Table A7.6. Mean ±SD linear and angular induced segment accelerations at the peak vertical force event of the 19<sup>th</sup> step.

	Joint I [norm	Moment nalised]						Linea	r induce	d accele	erations	[m⋅s <sup>-2</sup> ]								Ang	jular indu	iced acc	eleration	s [rad∙s⁻²	]	
	-			Rear	Foot			Sh	ank			Th	igh			Н	AT		Rear	Foot	Sha	ank	Thi	gh	HA	λT
			Horiz	ontal	Vert	ical	Horiz	ontal	Vert	cal	Horiz	ontal	Vert	ical	Horiz	ontal	Vert	tical								
	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD
MTP	0.00	0.01	-0.65	2.34	-0.84	3.05	-1.82	6.60	-1.26	4.56	-0.73	2.64	-0.60	2.16	0.10	0.38	-0.21	0.76	14.41	52.23	3.04	11.02	-6.29	22.82	1.10	3.98
Ankle	0.22	0.05	53.13	9.93	54.09	13.84	108.09	24.37	97.23	13.63	24.43	13.85	58.41	5.20	-9.93	2.32	30.48	6.17	-954.02	169.19	-102.81	67.10	388.12	79.35	-109.31	14.32
Knee	0.10	0.05	-21.33	12.09	-22.76	14.06	-63.85	35.96	-31.74	16.27	-28.28	15.80	-3.78	2.27	4.89	3.15	9.54	4.57	380.97	192.70	137.78	84.32	-225.39	131.11	19.56	15.14
Hip	0.10	0.08	-16.41	14.50	-15.95	14.35	-40.25	32.92	-27.72	22.86	-4.43	5.40	-9.28	8.06	3.47	3.08	5.52	4.44	296.22	234.33	63.78	57.53	-179.10	144.75	76.25	61.08
N 1												/ 1														

- Negative value represents a backward or downward a linear and clockwise angular (shaded cells) induced acceleration.

#### Table A7.7. Mean ±SD linear and angular induced segment accelerations at the peak propulsive force event of the third step.

	Joint M [norma	loment alised]						Linear	induced	laccele	erations	[m·s <sup>-2</sup> ]								Ang	ular indu	iced acc	eleration	s [rad∙s⁻²	]	
				Rear	Foot			Sha	nk			Thi	gh			HA	٩T		Rear	Foot	Sha	ank	Thi	gh	HA	λT
			Horiz	ontal	Vert	tical	Horiz	ontal	Ver	tical	Horiz	ontal	Verti	cal	Horizo	ontal	Vert	tical								
	Mean	± SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD
MTP	0.03	0.01	-10.10	4.57	-5.12	2.40	-22.88	9.45	-2.87	2.11	-9.34	3.84	-1.94	0.90	-0.10	0.33	-2.05	0.67	132.94	61.10	33.04	11.74	-65.88	23.17	10.43	3.86
Ankle	0.16	0.02	45.08	11.49	23.07	7.02	92.61	21.75	25.39	8.74	32.74	8.09	28.83	7.14	4.50	2.24	19.15	2.07	-590.68	143.33	-82.95	25.00	265.11	54.35	-80.12	20.97
Knee	0.02	0.02	-7.17	7.17	-3.53	3.37	-17.53	16.84	0.09	1.32	-6.55	6.25	2.26	2.14	2.14	2.07	1.30	1.33	92.56	94.11	32.76	29.37	-55.41	51.14	4.39	5.10
Hip	0.03	0.08	-7.21	17.51	-3.85	10.09	-15.41	39.32	-3.63	8.05	-2.50	8.39	-3.14	6.94	1.86	4.87	1.33	2.82	91.21	232.48	16.66	58.09	-53.70	143.66	22.04	57.31

Table A7.8. Mean ±SD linear and angular induced segment accelerations at the peak propulsive force event of the ninth step.

	Joint M [norma	oment llised]						Linear	induced	d accele	erations	[m⋅s <sup>-2</sup> ]								Ang	ular indu	ced acc	eleration	s [rad∙s <sup>-2</sup>	]	
				Rear	Foot			Sha	ank			Thi	gh			HA	٩T		Rear	Foot	Sha	ank	Thi	gh	HA	λT
			Horiz	ontal	Ver	tical	Horiz	ontal	Vert	ical	Horiz	ontal	Verti	cal	Horiz	ontal	Vert	tical								
	Mean	± SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD
MTP	0.03	0.01	-12.73	4.36	-6.32	1.74	-28.27	8.10	-5.37	2.30	-11.19	3.00	-2.84	1.17	0.20	0.34	-2.61	0.72	166.24	49.18	34.02	9.71	-82.76	21.21	10.19	3.45
Ankle	0.16	0.01	50.02	14.33	25.13	5.49	102.66	24.72	30.71	8.52	35.41	7.94	26.80	5.24	1.55	2.26	20.95	2.78	-657.78	166.70	-81.62	17.78	300.09	69.15	-63.61	21.00
Knee	0.03	0.03	-8.56	9.60	-3.86	3.96	-20.09	21.17	-1.43	2.42	-6.73	7.11	1.71	1.62	2.25	2.40	2.05	2.33	108.63	119.24	30.51	27.98	-66.44	68.35	7.87	8.50
Hip	0.03	0.03	-4.88	20.09	-2.57	10.11	-8.77	44.91	-4.70	8.54	-1.88	5.54	-3.20	6.05	1.06	4.57	1.23	2.81	63.37	255.26	-1.37	65.43	-23.61	182.36	11.88	74.34

#### Table A7.9. Mean ±SD linear and angular induced segment accelerations at the peak propulsive force event of the 19<sup>th</sup> step.

	Joint M [norma	loment alised]						Linea	r induce	d accel	erations	[m⋅s⁻²]								Ang	gular indu	uced acc	celeration	ls [rad∙s <sup>-:</sup>	<sup>2</sup> ]	
				Rear	Foot			Sh	ank			Thi	gh			HA	λT		Rea	r Foot	Sh	ank	Th	igh	H.	AT
			Horiz	ontal	Vert	ical	Horizo	ontal	Vert	ical	Horizo	ontal	Verti	cal	Horizo	ontal	Vert	ical								
	Mean	± SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD
MTP	0.03	0.02	-10.65	5.72	-5.68	3.09	-25.12	12.53	-4.62	3.20	-10.83	5.26	-2.24	1.30	0.15	0.41	-3.23	1.71	139.70	71.47	34.16	17.19	-72.97	35.02	5.29	3.84
Ankle	0.16	0.02	41.89	11.58	22.41	7.13	88.33	23.36	27.55	8.18	35.60	6.98	23.03	3.21	1.29	2.40	24.87	2.95	-547.21	144.55	-76.76	31.11	242.37	71.18	-25.20	19.48
Knee	0.03	0.03	-8.26	6.85	-4.34	3.69	-21.35	17.82	-1.47	1.95	-7.01	6.06	2.20	2.06	2.20	1.84	2.02	1.67	106.19	87.56	37.50	33.20	-74.32	64.34	12.50	11.26
Hip	-0.01	0.07	-0.01	12.98	0.38	8.57	3.83	37.34	-2.44	4.33	1.04	4.69	-1.82	2.32	-0.41	3.55	0.51	1.01	-1.16	175.60	-19.60	79.80	25.36	169.99	-8.82	69.48

- Negative value represents a backward or downward a linear and clockwise angular (shaded cells) induced acceleration.

# Appendix A8 - Example Participant information sheets and written informed consent form

Ethical approved was gained from the University Research Ethics Committee. Appendix A7 contains example participant information sheets and written informed consent form. These forms were provided to all athletes that participated in the studies within this thesis. The consent form was used to obtain written informed consent from each athlete prior to testing.

#### Participant Information Sheet

Project Title: Quantification of the underlying kinetic and kinematic characteristics during a maximal 40 metre sprint from starting blocks.

Principle Investigator: Hans von Lieres und Wilkau Supervisors: Dr Ian Bezodis & Prof Gareth Irwin Contact Details:

#### Purpose of this information sheet:

This document has been given to you to disclose information about this research project; its aim is to help you to reach a decision about whether or not you would like to participate. Before an explanation of the research is given, it is important for you to realise that participation in the study is entirely voluntary and should you decide to participate, you will have the right to withdraw at any time without the need to provide a reason.

#### What type of participants are we hoping to use in the study?

This study requires experienced male and female junior (16-18 years) and senior (18+ years) sprinters (male = sub 11 s for 100 m or sub 7 s for 60 m; female = sub 12 s for 100m or sub 8 s for 60 m). You must be free of injury at the time of testing.

#### Research background:

The ability to acceleration out of the blocks to maximal velocity has been shown to be of high importance in achieving high performances during the event. My previous study identified three key phases during the acceleration phase of a sprint. These are the initial, transition, and late acceleration phases. Previous research suggested that a number key technical changes occur during the acceleration phase but little is known about the characteristics of these changes. These technical changes include, changes in magnitude and direction of force application, changes in musculoskeletal demands at the ankle, knee and hip joint as well as changes in centre of mass height, increasing step length, step frequency, decreasing contact times and increasing flight times.

#### Aims of the research:

The main aim of this research is to quantify biomechanical changes during acceleration by assessing the characteristics of the steps in the initial acceleration, transition and late acceleration phases. This will be based on a thorough analysis of technique and forces during ground contact.

#### What will happen once you agree to participate in the study?

Data collection will take place in NIAC and consist of repeat sessions in order to collect data from steps in the initial acceleration, transition and late acceleration phases. The testing session will last one hour during which time during which time you will be asked to complete up to ten maximal sprint runs of up to 40 m from starting blocks with full recovery between trials. These will be filmed by a number of cameras and this data will be analysed later. Furthermore, ground reaction forces during the steps of interest will be collected using Kistler force platforms imbedded in the ground. The data collection will be non-intrusive and you will not be asked to complete any task that does not constitute part of your normal training session.

#### What are the risks of participating in the study?

The tasks which you will be required to perform will be no more strenuous than those that are executed in a normal training session. While there are risks associated with maximal sprinting, the participants who fall within the selection criteria of this study should have achieved a good level of technical competence as well as physical conditioning. Further to this a qualified sprints coach will be present at all data collections.

#### Your rights:

You are in no way obliged to participate in this study and there will be no implications should you chose not to participate. Agreeing to participate in this study does not mean you give up any legal rights. In the very unlikely event of something going wrong, Cardiff Metropolitan University fully indemnifies its staff, and participants are covered by insurance.

#### Benefits to you, the participant:

There will be no direct benefit from participating in this study.

#### Benefits to us, the research team:

The main benefit of completing this research is providing information regarding the biomechanics of the acceleration phase of sprinting. The research will give valuable information for biomechanists and sprints coaches.

#### What will happen to the data and information collected during the study?

The data will be analysed and stored using a coded format; therefore, all participants will be anonymous within the data. Following analysis, copies of your individualised results will be made available to you. Participant performance data will only be accessible by the research team, and so total confidentiality will be kept. The coded copies of all data will be stored in a secure holding location for 5 years, during which time, only the research team will be able to access it.

#### What next?

If you have any questions or concerns, please contact me on the e-mail address or phone number provided. If you are happy to participate in the study please complete the attached informed consent form. I will then contact you to confirm your availability for specific test dates.

On behalf of all researchers involved

Many thanks, Hans von Lieres und Wilkau BSc, MSc

#### Participant Informed Consent Form

# Title of Project: Quantification of the underlying kinetic and kinematic characteristics during a maximal 40 metre sprint from starting blocks.

Name of Researchers: Hans von Lieres, Dr Ian Bezodis, Prof Gareth Irwin

Participant to complete this section: each box.

Please initial

- 1. I confirm that I have read and understand all of the information included in the sheet titled 'Participant Information Sheet'. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.
- 2. I understand that the participation is voluntary and that it is possible to stop taking part at any time without giving a reason.
- 3. I understand that if this happens, my relationship with Cardiff Metropolitan University and my legal rights will not be affected.
- 4. I understand that information from the study may be used for reporting purposes, but that I will not be identified.
- 5. I have chosen and agree to take part in this research.
- 6. I am happy with pictures and video footage being taken and that these pictures can be used for presentation purposes in an anonymous way.

Date
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Signature of person taking consent

\* When completed, one copy for participant and one copy for researcher's files.