A BIOMECHANICAL FRAMEWORK OF THE TRAINING PRINCIPLES TO INFORM EXERCISE SELECTION WITHIN STRENGTH AND CONDITIONING FOR SPRINTING

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A thesis submitted for the degree of Doctor of Philosophy

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STATEMENT 1

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ABSTRACT

A BIOMECHANICAL FRAMEWORK OF THE TRAINING PRINCIPLES TO INFORM EXERCISE SELECTION WITHIN STRENGTH AND CONDITIONING FOR SPRINTING

Adam Brazil, Cardiff Metropolitan University, Cardiff, 2018

An essential component of physical preparation for sprinting is the selection of effective training exercises, with practitioners balancing the key training principles of overload and specificity to inform their decisions. However, exercise selection is often undertaken with little biomechanical underpinning. The aim of this research was therefore to apply biomechanical analyses and dynamical systems theory to advance understanding of the training principles of overload and specificity within exercise selection.

To achieve the overall research aim, the biomechanics of a competitive motor task (the block start in athletic sprinting) were investigated in detail (Phase 1. Technique Analysis: Biomechanics) and evaluated against a range of training exercises (Phase 2. Training Principles: Biomechanics Interface) within a sample of national and international male sprinters. A holistic account of the block start revealed novel insight to the key joint kinetic determinants of block start performance, and the emergence of proximal and in-phase extension joint coordination patterns that were linked to task execution. When evaluating training exercises, specificity in joint coordination was demonstrated across both traditionally viewed ‘general’ and ‘specific’ exercises. In addition, all exercises were shown to elicit musculoskeletal overload, although this was shown to be dependent on the biomechanical determinant of performance and individual athlete.

The current research encouraged a reconceptualisation of the principle of specificity within exercise selection, by demonstrating that exercise selection should not solely be based on the replication of a competitive motor task. Instead, exercise selection must consider how the musculoskeletal determinants of performance are overloaded, in addition to the replication of task specific coordination patterns. The work of this thesis successfully developed a framework to facilitate evidence-based decisions within exercise selection, by embedding biomechanical analyses and the model of constraints (Newell, 1986), within the principles of training.
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International Conference Articles:


National Conference Articles
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NOMENCLATURE AND DEFINITIONS

Abbreviations used for key terminology throughout the thesis

CM  Centre of Mass
COP Centre of Pressure
M  Extensor Joint Moment
P  Positive Extensor Joint Power
VC  Vector Coding
CRP  Continuous Relative Phase
CA  Coupling Angle
CAV  Coupling Angle Variability
ANK  Ankle Joint
KNE  Knee Joint
HIP  Hip Joint

Definitions of key terms used throughout the thesis

Biomechanics  The application of mechanical principles to the biological system.

Technique  A strategy used to achieve a task, which can be described at different levels (kinematic, kinetic) and dimensions (single joint, coordination).

Competitive Motor Task  A series of organised movements in which the outcome of action results in the performance of a sports skill.

Coordination  The relation between components within a system to achieve a task.

Strength Training  The process of imposing physical loading to enhance the capability of the neuromuscular system to produce force.
CHAPTER 1: INTRODUCTION

1.1 Research Overview

For athletes within sports that require maximal effort over a short period of time (i.e. sprint events), training methods external to the sport itself are widely employed, with the goal of developing neuromuscular strength that can increase performance (Siff, 2003). According to the principles of training (Dick, 2002; Matveyev, 1981; Siff & Verkoshansky, 1999), a training exercise should impose a greater stress on the biological system than is experienced in competition (overload). In addition, as subsequent adaptations are specific to the nature of the training stress (specificity), training exercises must possess relevant biomechanical similarity with a competitive motor task. In practice, strength and conditioning practitioners balance these principles of training to select exercises to enhance sports performance. However, decisions are often based on the principle of specificity alone, viewed as replicating gross movement patterns and velocity (Moir, Brimmer, Snyder, Connaboy, & Lamont, 2018). Currently, there is a lack of biomechanical evidence to inform decisions for exercise selection within strength and conditioning for sprinting (Bolger, Lyons, Harrison, & Kenny, 2016).

The short sprint events in athletics (60 m, 100 m, 200 m) often receive large amounts of public attention, with athletes performing at the limit of human locomotion. The goal of these events is to cover the predetermined distance in minimal time, with the optimal strategy suggested to be to minimise the time spent running at submaximal velocity (van Ingen Schenau, de Koning & de Groot, 1994). The importance of acceleration to success in the short sprint events is therefore paramount, and there is no greater acceleration elicited than in the starting block phase, as an athlete attempts to accelerate from the stationary ‘set’ position (Mann, 2007). The significance of the block start to overall 100 m sprint performance has been established (Willwacher et al., 2016), supporting the interest of researchers to undertake biomechanical analyses to understand block start technique and the characteristics related to performance outcome (Bezodis, Salo, & Trewartha, 2015; Mero, Kuitunen, Harland, Kyröläinen, & Komi, 2006; Otsuka et al., 2014; Slawinski, Bonnefoy, Ontanón, et al., 2010).

Despite the common prescription of supplementary strength and conditioning training in sprint athletes’ training programmes (Bolger et al., 2016; Burnie et al.,
2017; Moir et al., 2018), empirical evidence has not reached consensus on the best methods for enhancing sprint performance (Cormie, McGuigan, & Newton, 2011b; Rumpf, Lockie, Cronin, & Jalilvand, 2016). Whilst heavy resistance training can improve neuromuscular strength (Suchomel, Nimphius, Bellon, & Stone, 2018) and athletic performance (Cormie et al., 2011b; Suchomel, Nimphius, & Stone, 2016), coaches often perceive these exercises to be non-specific and employ more specific methods to assist the transfer of increased neuromuscular potential to enhanced sports performance (Burnie et al., 2017; Bolger et al., 2016). Within sprinting, the specificity of a training exercise is often determined based on the replication of gross movement pattern and velocity (Bondarchuck, 2007; Crick, 2009; Wild, Bezodis, Blagrove, & Bezodis, 2011; Young, Benton, Duthie, & Pryor, 2001). However, this approach to specificity devalues the importance of heavy resistance methods that have an indirect influence on sports performance, by overloading the specific biomechanical determinants of performance (Siff & Verkoshansky, 1999; Moir et al., 2018).

Coach perception (Bolger et al., 2016; Burnie et al., 2017) and empirical evidence (McBride, Triplett-McBride, Davie, & Newton, 2002; Siff & Verkoshansky, 1999; Wilson, Murphy, & Walsh, 1996) has suggested that similarity in movement patterns can facilitate sport specific adaptations to resistance training and the transfer of training to improved sports performance (Bondarchuck, 2007; Young, 2006). However, few studies have approached movement specificity from a dynamical systems theory perspective. Dynamical systems theory is embedded in motor control theory, explaining how movement emerges through a process of self-organisation based on the intentions of the performer and the constraints imposed on the biological system (Kelso, 1995; Kugler, Kelso, & Turvey, 1980; Newell, 1986). In this context, movement is often analysed through the coordination of functionally linked segments or joints (Hamill, van Emmerik, Heiderscheit, & Li., 1999), defined as the patterning of body and limb motions (Turvey, 1990). Greater insight into the similarity in movement between a training and competitive motor task may thus be achieved by adopting a dynamical systems approach to human movement (Wilson, Simpson, & Hamill, 2009). Furthermore, the framework of constraints on action (Newell, 1986) may provide theoretical basis for how the principles of training (overload and specificity) can develop unique organismic constraints in order for a task to be executed to a higher level of performance.
Whilst biomechanical investigations within gymnastics have combined traditional biomechanical technique analysis (joint kinematics and kinetics) alongside movement coordination (Irwin & Kerwin, 2005; 2007a; 2007b) to evaluate training drills, a lack of evidence exists within strength and conditioning for sprinting. The merging of biomechanics with dynamical systems theory provides an avenue for understanding how an athlete may adapt to training, influencing practical solutions for selecting training exercises to enhance sports performance.

1.2 Statement of Research Aim and Purpose
There is currently limited evidence that has explored the principles of training (Matveyev, 1981; Siff & Verkoshansky, 1999) within the theoretical framework of constraints (Newell, 1986) to aid practitioners to make informed decisions when selecting training exercises. As such, the aim of this research was to apply biomechanical analyses and dynamical systems theory to advance understanding of the training principles of overload and specificity within exercise selection. The overall purpose was to provide a conceptual framework for evaluating training exercises, to facilitate evidence based decisions when selecting exercises to enhance sports performance. Achieving the research aim and purpose will offer practitioners greater insight when developing and evaluating training exercises that are employed to increase sports performance.

In order to undertake the current research, the block start in athletic sprinting was used as the competitive motor task to enhance theoretical and conceptual understanding of exercise selection within strength and conditioning. To address the aim of the thesis, a two-phase approach was adopted: **Technique Analysis: Biomechanics** (Phase 1) and **Training Principles: Biomechanics Interface** (Phase 2). Across the two phases, nine research questions were formulated to achieve the overall research aim and were addressed in specific studies detailed in Chapters 3-5. A research overview is provided in Figure 1.1, detailing the overall thesis aim and purpose, the organisation of each research question, and the specific studies employed to address the research questions.
A BIOMECHANICAL FRAMEWORK OF THE TRAINING PRINCIPLES TO INFORM
EXERCISE SELECTION WITHIN STRENGTH AND CONDITIONING FOR SPRINTING

**Thesis Aim**
To apply biomechanical analyses and dynamical systems theory to advance understanding of the training principles of overload and specificity within exercise selection

**Thesis Purpose**
To provide a conceptual framework for evaluating training exercises, to facilitate evidence based decisions when selecting exercises to enhance sports performance

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### Phase 1: Technique Analysis: Biomechanics

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### Phase 2: Training Principles: Biomechanics Interface

| Chapter 4: An Intra-Limb Joint Coordination and Coordination Variability Analysis of Block Start Technique |
| **Aim** | To quantify intra-limb joint coordination and variability during the execution of the block start and understand whether joint coordination and coordination variability is influenced by performance level. |
| **Purpose** | To provide novel understanding of movement dynamics in the block start, extending conventional biomechanical technique analysis to encompass the coordinated nature of human movement from a dynamical systems perspective. |
| **Research Questions** |
| RQ5: What are the patterns of intra-limb joint coordination and coordination variability when executing the block start? |
| RQ6: How are the intra-limb joint coordination patterns observed when executing the block start affected by the level of performer? |
| RQ7: How is intra-limb joint coordination variability influenced by the level of performer? |

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### Chapter 5: A Biomechanical Evaluation of Training Exercises for Enhancing Block Start Performance

| **Aim** | To evaluate characteristics of musculoskeletal demand and movement dynamics for a range of training exercises in reference to the block start |
| **Purpose** | To inform objectivity within exercise selection and contribute to theoretical understanding of the principles of training. |
| **Research Questions** |
| RQ8: How do lower limb joint kinematics and kinetics compare between the block start and traditionally viewed general and more specific training exercises? |
| RQ9: How does intra-limb joint coordination and coordination variability compare between the block start and traditionally viewed general and more specific training exercises? |

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### Chapter 6: General Discussion

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**Figure 1.1. Research Overview.**
1.3 Development of Research Questions
Possessing a biomechanical understanding of a competitive motor task is crucial to ensure training is most relevant to the sport and influences the way that coaches select training exercises (Irwin, Hanton, & Kerwin, 2005; Moir et al., 2018; Siff & Verkoshansky, 1999). The requirement for understanding the biomechanics of a competitive motor task formed the basis of Phase 1 of the current research.

Phase 1: Technique Analysis: Biomechanics
From a biomechanical perspective, empirical studies have increased understanding of block start technique, through analyses of external kinetics (Otsuka et al., 2014; Willwacher et al., 2016), joint kinematics (Bezodis et al., 2015) and joint kinetics (Mero et al., 2016). However, joint kinetic data during the block start have not yet been fully quantified, and previous analyses have been conducted in isolation. To address these limitations, the first research question was established:

**Research Question 1 – What are the external kinetic and lower limb joint kinematic and kinetic characteristics of executing the block start?**

In order to increase knowledge and understanding of the techniques used to satisfy the task demands of executing the block start, an external kinetic and joint kinematic and kinetic analysis of technique was performed. Answering this question could provide novel insight into the musculoskeletal demand of executing the block start. To address biomechanical differences between the front and rear leg, the second research question was formed:

**Research Question 2 – How are the biomechanics of the block start different between the front and rear block/ leg?**

Previous research has sought to determine the strategies associated with superior block start performance, often focusing on external kinetics (Fortier, Basset, Mbourou, Favieral, & Teasdale, 2005; Otsuka et al., 2014; Willwacher, Herrmann, Heinrich, & Brüggerman, 2013; Willwacher et al., 2016). These investigations have revealed a range of external kinetic variables associated with block start performance. To provide clarity on the key external kinetic determinants of block start performance within the current study, the next research question emerged:
Research Question 3 – Which external kinetic variables are associated with higher levels of block performance?

Although external kinetic analyses provide valuable insight into starting block performance (Willwacher et al., 2016), analysis of joint kinetics allow for increased understanding of the causes of segment motion that are responsible for centre of mass acceleration from the set position. In an attempt to provide novel insight into the lower limb joint kinetic strategies associated with superior block performance, the fourth research question was asked:

Research Question 4 – What are the relationships between lower limb joint kinetics, external kinetics and starting block performance?

Research Questions 1-4 formed Chapter 3 of the thesis, of which the aim was to investigate the biomechanical demand of executing the block start and the kinetic determinants of performance. The purpose of Chapter 3 was to increase understanding of the biomechanics of the block start and key characteristics of successful performance, to add valuable and novel information to the body of knowledge of the sprint start. The knowledge gained would help develop coaches’ conceptual understanding of block start technique, alongside the appraisal of training exercises against the biomechanical determinants of performance.

Dynamical systems theory proposes that movement arises from self-organisation in response to imposed constraints on action (Newell, 1986), through which patterns of coordination emerge to satisfy the demands of the task (Kugler et al., 1980; Glazier, 2015; Turvey, 1990). Understanding these coordination patterns and their inherent variability can provide valuable insight into the organisation and control of movement during motor tasks (van Emmerik, Hamill, & McDermott, 2005). To extend beyond a traditional biomechanical analysis (Chapter 3), a dynamical systems approach was adopted to further understand block start technique, and formed the next research question:

Research Question 5 – What are the patterns of intra-limb joint coordination and coordination variability when executing the block start?
The redundancy in biological degrees of freedom (Bernstein, 1967) provides individuals with the opportunity to achieve the same motor task utilising different coordination solutions (James & Bates, 1997). To understand the possibility for individual differences in coordination patterns exhibited in the block start, and to understand whether individuals of higher performance levels demonstrated unique techniques, research question six was formed:

**Research Question 6 – How are the intra-limb joint coordination patterns observed when executing the block start affected by the level of performer?**

Coordination variability is a fundamental feature of dynamical systems theory and is inherent in human movement (Hamill, Haddad, & McDermott, 2000). Empirical studies have evidenced that increased variability can be observed in expert performers (Wilson, Simpson, van Emmerik, & Hamill, 2008), providing the flexibility to explore coordination solutions to maintain task performance under varying constraints (Bartlett, Wheat, & Robbins 2007; Glazier & Davids, 2009). To continue building knowledge of the characteristics of higher levels of task performance, the next research question was posed:

**Research Question 7 – How is intra-limb joint coordination variability influenced by the level of performer?**

Research Questions 5-7 formed Chapter 4 of the thesis, of which the aim was to quantify intra-limb joint coordination and variability during the execution of the block start and understand whether joint coordination and coordination variability is influenced by performance level. The purpose of Chapter 4 was to provide novel understanding of movement dynamics in the block start, extending conventional biomechanical technique analysis to encompass the coordinated nature of human movement. The knowledge gained would further assist conceptual understanding of block start technique and the evaluation of training exercises to satisfy the requirement of movement similarity to ensure sport specific adaptations (Irwin & Kerwin, 2007a; Siff & Verkoshansky, 1999; Wilson et al., 1996; Young, 2006).

The principles of training dictate that a training exercise must impose stress on the biological system (overload) in a way that is specific to the competitive motor task (specificity) in order to facilitate sport-specific adaptations that can enhance
performance (Matveyev, 1981; Siff & Verkoshansky, 1999). Utilising the knowledge formed in Phase 1, Phase 2 continued to investigate the principles of overload and specificity within exercise selection for enhancing sports performance.

**Phase 2: Training Principles: Biomechanics Interface**

Previous research explicit to the block start has explored the biomechanics of training principles from a joint kinematic and external kinetic perspective (Okkonen & Hakkinen, 2013). However, other research in sprinting (Irwin, Kerwin, Rosenblatt, & Wiltshire, 2007) and gymnastics (Irwin & Kerwin, 2007b) has utilised joint kinetic analyses to infer greater detail of overload and the nature of possible physiological adaptation. Whilst joint moment and power can be utilised to infer the magnitude of overload, it is known that adaptations are specific to the nature of imposed stress (Siff & Verkoshansky, 1999). One of the key mediators of specific adaptations is the similarity in joint angle (Morrissey, Harman, & Johnson, 1995; Rhea et al., 2016). Taking a joint level approach to understand the overloading nature of training exercises with respect to a competitive motor task, research question 8 was formed:

**Research Question 8 – How do lower limb joint kinematics and kinetics compare between the block start and traditionally viewed general and specific training exercises?**

Similarity in movement pattern (movement specificity) has often been regarded as the primary factor influencing the transfer of training to improved sports performance (McBride et al., 2002; Siff & Verkoshansky, 1999; Wilson et al., 1996; Young, 2006). However, few studies have utilised dynamical systems theory of movement coordination and variability to understand movement specificity (Romanazzi, Galante, & Sforza, 2015; Wilson et al., 2009). As such, the final research question was developed to address this limitation:

**Research Question 9 – How does intra-limb joint coordination and coordination variability compare between the block start and traditionally viewed general and specific training exercises?**

Research questions 8 and 9 formed Chapter 5 of the thesis, of which the aim was to evaluate characteristics of musculoskeletal demand and movement dynamics for a range of training exercises in reference to the block start. The purpose of Chapter
5 was to inform objectivity within exercise selection and contribute to theoretical understanding of the principles of training. The knowledge gained helped to develop a conceptual framework for exercise selection, by considering the principles of training (Matveyev, 1981; Siff & Verkoshansky, 1999) from a constraints based approach to human movement (Davids, Glazier, Araujo, & Bartlett, 2003; Moir et al., 2018; Newell, 1986).

The two research phases and nine research questions provided context to guide the progression of research and development of new knowledge, to achieve the overall aim. Overall, three studies (Chapters 3 to 5) were constructed and are overviewed in section 1.4.

1.4 Organisation of Thesis Chapters

1.4.1 Chapter 2 – Review of Literature
Chapter 2 discussed and critiqued existing literature from sprint biomechanics, the principles of training and motor control that is relevant to understanding the biomechanical underpinnings of exercise selection. To begin with, training theory was introduced and discussed with particular interest on the categorisation of exercises within strength and conditioning and determining an exercises level of specificity. The competitive motor task, the block start in athletic sprinting, was then introduced and relevant biomechanics literature was discussed. Particular attention was directed toward the kinematics and kinetics of the block start and sprint acceleration to provide an overview of the competitive motor task and areas for future investigation.

Finally, dynamical systems theory of motor control was reviewed with a final focus on how the underlying principles of self-organisation of movement coordination may influence the principles of training. Selected literature concerned with relevant methodological approaches were also discussed. The review of literature presented in Chapter 2 underpinned the development of the overall research aim and two phases.
1.4.2 Chapter 3 – A Biomechanical Analysis of Block Start Technique

Phase 1 of the thesis, to increase conceptual understanding of block start technique was initiated in Chapter 3. Within Chapter 3, traditional biomechanical analysis of kinematics and kinetics was undertaken, including the quantification of musculoskeletal demand of the competitive motor task. In addition, the strategies associated with superior block start performance were investigated. The findings of Chapter 3 provided a foundation of knowledge to be used when evaluating training exercises in Chapter 5.

1.4.3 Chapter 4 – An Intra-Limb Joint Coordination and Coordination Variability Analysis of Block Start Technique

Continuing Phase 1, Chapter 4 utilised dynamical systems theory to increase understanding of block start technique through analysis of intra-limb joint coordination and variability. Vector coding methods were used to quantify joint coordination and variability during the block start. Further analysis was undertaken to investigate whether higher levels of block performance were associated with specific coordination patterns or magnitudes of coordination variability. The findings of Chapter 4 added to the foundation of knowledge obtained in Chapter 3, to be used when evaluating the requirement of movement specificity in training exercises in Chapter 5.

1.4.4 Chapter 5 – A Biomechanical Evaluation of Training Exercises For Enhancing Block Start Performance.

Chapter 5 encompassed Phase 2 of the thesis: to explore the interface between biomechanics, motor control and the principles of training to provide an evidence based framework for exercise selection within strength and conditioning. Utilising the knowledge gained through Chapters 3 and 4, a range of exercises were evaluated against the block start with respect to the principles of overload and specificity. Using discrete and continuous analyses, each training exercise was compared against the block start focusing on two key themes: musculoskeletal demand (Chapter 3) and movement dynamics (Chapter 4). Results were interpreted to provide recommendations for exercise selection practice, and a framework for evaluating a training exercise against a competitive motor task emerged.
1.4.5 Chapter 6 – General Discussion

Chapter 6 discussed the findings of Chapters 3 to 5 and the nine specific research questions posed in section 1.3, in the context of the main theories explored in the current research. The novel contributions to knowledge and practical implications of this research to sports biomechanics and strength and conditioning practice were discussed following an appraisal of key methodologies.

A research philosophy emerged throughout Chapter 6 that explored the importance of biomechanics in unlocking the mechanisms underlying effective exercise selection. Based on the findings of the current research, a reconceptualisation of what constitutes a ‘sport specific’ exercise was stimulated, and a novel framework to inform objective decisions within exercise selection was presented. Chapter 6 concluded with directions for future research study.
CHAPTER 2: REVIEW OF LITERATURE

2.1 Introduction
This aim of this chapter was to discuss and critique existing literature from training theory, motor control and sport biomechanics that is relevant to understanding how the principles of training can be used to select exercises in order to enhance athletic performance. To achieve this aim, the history of training theory with attention to the principles of overload and specificity were reviewed with special attention to training methods for enhancing sprint performance. As biomechanical understanding is essential for exercise selection, the block start in athletic sprinting was introduced as the competitive motor task for this research, with literature discussed that has analysed the biomechanics of block start technique. Dynamical systems theory of motor control was then reviewed, focusing on the application of Newell’s (Newell, 1986) model of constraints and intra-limb coordination analysis to the principles of training within exercise selection. Relevant gaps in the literature were highlighted and methodological considerations for the analysis of sports tasks were discussed. Conducting a review of literature facilitated the development of research questions that guided the investigations detailed within Chapters 3-6.

2.2 Training Theory: Strength Training

2.2.1 Introduction to Strength Training
Muscular strength can be defined as the ability to exert force to overcome resistance under given conditions (Baker, 2014; Siff, 2000). Within a sporting context, an athlete may have to exert large forces in order to manipulate their own body mass (e.g. sprinting) or manipulate an external body (e.g. weightlifting). Therefore, possessing high levels of muscular strength has been established as a fundamental component of elite performance (Siff & Verkoshansky, 1999; Stone & Stone, 2011; Zatsiorsky & Kraemer, 2006). Strength training, viewed as the process of imposing physical loading to enhance the capability of the neuromuscular-skeletal system to produce force (Siff, 2003), is thus recognised as a vital component in the physical preparation of athletes (Baker, 1996; Cormie et al., 2011b; Hansen, 2014; Moir et al., 2018; Newton & Kraemer, 1994; Suchomel et al., 2016). The purpose of incorporating strength training methods into the training programme of athletes is to enhance the ability to express force in a competitive motor task through the
development of underpinning neuromuscular-skeletal properties that establish and athletes ‘motor potential’ (Dick, 2002; Zatsiorsky & Kraemer, 2006; Siff, 2003; Verkoshansky, 2011). Based on the foundations of biological adaptation to imposed stress (Selye, 1936), a strength training exercise must exceed an athlete’s habitual level of stress (overload) and stimulate adaptations that are specific to the competitive motor task (specificity), to be effective at enhancing sports performance (Matveyev, 1981; Siff & Verkoshansky, 1999). As a result, it is widely recognised that strength training programmes should be developed with a sound biomechanical understanding of the competitive motor task and needs of the individual athlete, to ensure that biological adaptations can successfully enhance athletic performance (Baker, 2014; Dick, 2002; Moir et al., 2018; Siff & Verkoshansky, 1999; Suchomel et al., 2018; Winkelman, 2009; Zatsiorsky & Kraemer, 2006).

2.2.2 The Importance of Strength in Athletic Performance

Whilst certain underlying factors underpinning athletic performance cannot be changed (e.g. genetics), an individual’s muscular strength can be altered with regular strength training (Suchomel et al., 2016). Muscular strength is considered to provide the foundation for high rates of force development (RFD) (Andersen & Aagard, 2006) and external mechanical power (Haff & Nimphius, 2012; Cormie, McGuigan, & Newton, 2011a), which are of utmost importance to sports performance (Stone & Stone, 2011). Many authors advocate that performance in ‘explosive’ type sports is determined by the ability to generate external mechanical power (Cronin & Sleivert, 2005; Kawaori & Haff, 2004; Siff, 2003; Stone & Stone, 2011), and recently the ability to generate external mechanical power has been identified as the best descriptor of sprint start performance (Bezodis et al., 2010). In a recent review article (Suchomel et al., 2016), the authors found that 44 out of 59 (75%) empirical studies investigating RFD and 116 out of 177 (65%) investigating external mechanical power, reported large correlation magnitudes (r ≥ 0.5) with maximal strength. Therefore, the significance of strength training to sports performance can be initially inferred through the development of underlying neuromuscular potential that are relevant to increasing the power output of the competitive motor task (Siff, 2003; Verkoshansky, 2011).

Whilst it is acknowledged that increasing neuromuscular potential alone does not guarantee sports performance enhancement (Bobbert & van Soest, 1994; Wilson et al., 1996; Young, 2006), many empirical studies have confirmed the importance of
maximum strength in a variety of sports tasks. These tasks have included sprint cycling (Stone et al., 2004), track and field throwing (Judge et al., 2011; Judge & Bellar, 2012), boxing punch impact force (Loturco et al., 2016), baseball bat speed (Reyes & Dolny, 2009) and rugby tackle ability (Speranza, Gabbett, Johnston, & Sheppard, 2015). With respect to sprinting, few studies have measured the influence of strength on elite sprint performance (Suchomel et al., 2016). However, empirical studies have confirmed the importance of maximal strength for sprint performance within a variety of sports (Seitz, Reyes, Tran, de Villarreal, & Haff, 2014). For example, utilising a sample of elite rugby players, Baker and Nance (1999) demonstrated that increased strength and power (assessed through the back squat and power clean exercise) were significantly associated with faster sprint times to 10 and 40 m distances.

From the above evidence, it is apparent that the ability to exert large magnitudes of force is beneficial to athletic performance in ‘explosive’ tasks, which is influenced by an athlete’s underlying neuromuscular potential (Newton & Kraemer, 1994; Stone & Stone, 2011). However, identifying the best strategies to promote specific adaptations to enhance an athlete’s neuromuscular potential and increase sports performance, remains a challenge for strength and conditioning practitioners and sports coaches (Cormie et al., 2011b; Burnie et al., 2017).

2.2.3 The Adaptation Process

Biological adaptation is a central component within traditional and modern theories of training (Matveyev, 1981; Siff & Verkoshansky, 1999; Cunanan et al., 2018) and can be described as an adjustment of an organism to its environment (Zatsiorsky, & Kraemer, 2006). To provide a mechanistic model to understand the relationship between stress and adaptation in biological organisms, pioneering scientist Hans Selye (Selye, 1936; 1951) established the general adaptation syndrome (GAS). The GAS model, initially developed in response to ‘diverse nocuous agents’ (Selye, 1936), describes that an organism aims to maintain homeostasis by responding to stress through a three-phase process of alarm, resistance, and exhaustion (Selye, 1951). Depicted in Figure 2.1, the GAS model explains that when an organism is exposed to a stress stimulus to the quality of intensity to which it is not adapted (Selye, 1938), there will be an initial decline in the organisms’ ability to cope with the stressor. Biological signalling will then provide resistance to the stressor and adaptation will occur, including biochemical, structural and perhaps psychological
adaptations (Stone, et al., 1982). Prolonged exposure to a stressor or a dose too high in magnitude can then result in exhaustion (Selye, 1951).

![Diagram of Selye's GAS model](image)

Figure 2.1. Schematic representation of Selye’s (Selye, 1936; 1951) General Adaptation Syndrome (GAS) model. Adapted from Cunanan et al. (2018).

The general adaptation syndrome model (Selye, 1936) has been widely adopted to explain the cause of sports performance enhancement through strength training, providing a conceptual framework for the link between stress, adaptation and fatigue. Based on the GAS model, training to improve sports performance must therefore cause adaptations that enhance the capability (neuromuscular potential) of an athlete to express force in a competitive motor task (Newton & Kraemer, 1994; Siff, 2003).

Several morphological and neuromuscular adaptations can occur in response to strength training, including changes in muscle cross sectional area, pennation angle, muscle-tendinous stiffness, fibre type, motor unit recruitment, firing frequency, motor unit synchronisation, and intra- and inter-muscular coordination (Behm, 1995; Folland & Williams, 2007; Sale, 2003; Suchomel et al., 2018). Whilst enhancing these neuromuscular-skeletal adaptations can provide an athlete with an increased neuromuscular potential, it is recognised that the utilisation of neuromuscular potential for a given competitive motor task is not guaranteed (Young, 2006). As recognised by Selye (1936; 1951), biological adaptation is specific to the nature of the stressor, an observation that has been widely investigated in the scientific literature to recommend the most effective training exercises to enhance athletic performance (Morrissey et al., 1995; Stone & Stone, 2011).
The GAS model has received criticism by contemporary training theorists, who mainly focus on its lack of acknowledgement to psychological and emotional responses to stress (Kiely, 2012). However, the fact remains that disturbance to the state of an organism is the driving force for biological adaptation, which is the central concept of the GAS model and the basis for its application to athletic training (Cunanan et al., 2018).

2.2.4 The Principles of Training
The GAS model (Selye, 1951) provided a conceptual framework to be applied to strength training (Matveyev, 1981; Stone et al., 1982), suggesting that strength training must provide systematic exposure to specific stressors, so relevant biological adaptations can occur that facilitate the enhancement in sports performance. The process of adaptation described by the GAS model (Selye, 1951) provided the basis to develop the principles of training (Matveyev, 1981; Siff Verkoshansky, 1999), that are applied in the creation of athletic training programmes.

Three main principles govern the training programmes of elite athlete: overload, specificity and variation (Newton & Kraemer, 2006). Variation, often named periodisation, is an important consideration for long-term athletic development, allowing a coach to fragment a continuum of time into manageable components, facilitating the acquisition and realisation of multiple neuromuscular qualities with a synergistic effect of improving sports performance (Bondarchuck, 2007; Cunanan et al., 2018). However, the principles of overload and specificity directly influence the selection of training exercises with the intention of enhancing sports performance (Moir et al., 2018), and are therefore most relevant to the current research.

2.2.4.1 Overload
The principle of overload is embedded in Selye’s general adaptation syndrome, describing that adaptation only occurs if an organism is exposed to a stimulus to the quality or intensity of which it is not adapted (Selye, 1936, 1951). In the context of strength training, overload has emerged as the heightening of a stressor to oblige the body to seek a higher status of adaptation (Dick, 2002). An overload stimulus has three main components, intensity, frequency and duration, which determine the overall biological stress (Stone, Plisk, & Collins, 2002). The intensity of an overload
stimulus is often regarded as most pertinent for increasing muscular strength (Cronin & Crewther, 2004), which is usually characterised by the amount of resistance provided by the training exercise in absolute magnitude and relative magnitude in relation to an athlete’s maximum (% 1RM). However, it has been argued that the intensity of an overload stimulus be defined within the intended adaptation, for example, overload for maximal strength and speed development would be inherently measured by different intensity parameters (load lifted vs. speed of movement, respectively) (Dick, 2002).

In the sporting context, overload has been interpreted to describe a mechanical stimulus greater than that observed in the competitive motor task (Siff, 2003). Often, overload has been estimated through the measurement of external force and power (Kawamori, Newton, & Nosaka, 2014; Okkonen & Hakkinen, 2013), with little attention to that at the joint level of mechanics (Irwin & Kerwin, 2007b, Irwin et al., 2007). It therefore appears that there is large scope to investigate overload between strength training exercises and a competitive motor task from a joint kinetic perspective.

2.2.4.2 Specificity
The principle of specificity is historically defined within the concept that adaptations to a given stressor are specific to the nature of the stressor (Dick, 2002; Matveyev, 1981; Selye, 1951; Siff, 2003; Siff & Verkoshansky, 1999; Stone et al., 2002; Zatsiorsky & Kraemer, 2006). Examples of specific adaptations to imposed stress have historically been demonstrated with respect to contraction type (Folland, Hawker, Leach, Little, & Jones, 2005), joint angle and angular range of motion (Graves, Pollock, Jones, Colvin, & Leggett, 1989; Kitai & Sale, 1989; Rhea et al., 2016; Weir et al., 1995), and velocity (Kanehisa & Miyashita, 1983; Morrissey et al., 1995).

Increases in strength are maximised at the joint angle evoked in training with respect to isometric (Folland et al., 2005; Kitai & Sale, 1989; Weir et al., 1995) and dynamic training (Graves et al., 1989; Rhea et al., 2016), with diminishing improvements found when moving further away from the trained angle. Residual increases have been found up to 30° from the trained joint angle during isometric knee extension (Weir et al., 1995), although the bandwidth of joint angle specific strength increases has yet to be identified when the training and testing task are inherently different.
Furthermore, empirical evidence has contested early observations of velocity specificity, by suggesting that the intention to move quickly may be as important as the actual movement velocity, for enhancing high velocity isokinetic strength (Behm & Sale, 1993) and performance in high velocity athletic tasks (Almasbakk & Hoff, 1996; Cronin, McNair, & Marshall, 2001).

Within contemporary training theory and practice, specificity is reflected in the similarity between a training exercise and sports task, with respect to bioenergetics and mechanics (Stone & Stone, 2011). Biomechanical specificity therefore refers to the degree of similarity between a training exercise and competitive motor task, often dealing with kinematic and kinetic associations such as movement pattern, external force, and velocity parameters (Siff & Verkoshansky, 1999; Stone et al., 2002; Stone & Stone, 2011). The degree of biomechanical specificity is therefore suggested to be the most important factor when selecting training exercises to enhance athletic performance, by increasing the probability of positive training transfer (Behm, 1995; Bondarchuck, 2007; Sheppard, 2003; Stone & Stone, 2011; Young, 2006).

The concept of training transfer has been extensively studied in scientific disciplines to describe how a response in one task affects the response in another (Issurin, 2013). Within a sporting context, training transfer can be expressed as a function of gain in performance relative to gain in the training exercise (Zatsiorsky & Kraemer, 2006). According to Bondarchuck (2007), there are three types of training transfer: positive, negative and neutral. Positive transfer occurs when there is a parallel increase in sports performance and training exercise, negative transfer describes the opposite direction, whilst neutral indicates there is no change in sports performance regardless of the change in the training exercise (Bondarchuck, 2007).

Siff & Verkoshansky (1999) argued that the basic mechanics, not necessarily the outwards appearance of training movements must be similar to those of the competitive motor task in order to maximise positive transfer, based on the specific nature of biological adaptation. The authors’ presented a number of criteria proposed to maximise the transfer of training, coined the principle of dynamic correspondence (Siff & Verkoshansky, 1999; Siff, 2003), including: the amplitude and direction of movement, joint angular region of peak force production, dynamics of the effort, the rate and time of maximum force production, and the regime of
muscular work. Dynamic correspondence (Siff & Verkoshansky, 1999; Siff, 2003) recognises the kinematic and kinetic features of specificity at both the external and joint levels of mechanics and suggests that increased satisfaction of all criteria will enhance the transfer of training.

2.2.4.3 Movement Specificity & the Transfer of Training

Although traditional theories of training recognised the importance of overload and specificity, contemporary perception amongst coaches is that positive transfer is maximised with replication of the competitive motor task (Bolger et al., 2016; Burnie et al., 2017; Wild et al., 2011). This view has been experimentally supported by investigations reporting that increased transfer occurs when the movement pattern between the training and testing task are similar. For example, Augustsson, Esko, Thomeé, and Syantesson (1998) found a significant difference in back squat 1RM improvements following six weeks of training with the back squat (31%) compared with isolated knee extensor and hip extensor machines (13%). Again, Wilson et al., 1996 found that eight weeks of strength training with the squat exercise resulted in concomitant 21% increases in 1RM strength and vertical jump height, but only 2.3% improvements in 40 m sprint performance were observed. Later, McBride et al. (2002) supported the concept of movement specificity for enhanced transfer of training, by finding that eight weeks of jump squat training with 30% 1RM increased jump height in the training task by 17% but no subsequent increases in 5 m or 10 m sprint performance was observed.

Mechanistic insight towards increased transfer of training in tasks that appear more similar to the competitive motor task has rarely extended beyond suggestions of increased similarity in gross movement patterns. However, based on the evidence by Augustsson et al. (1998), and other evidence supporting the use of multi-joint exercise compared with machine weights (Stone et al., 2002), the similarity in the interaction between working components of the biological system (i.e. coordination) could provide greater explanation towards the transfer of training effect. Coaches regularly acknowledge the importance of coordination for maximising transfer (Burnie et al., 2017) although there is limited evidence adopting intra-limb coordination approaches to quantify movement specificity. At the inter-muscular level, it has been shown that traditional strength training exercises (squat, deadlift, leg press) have very different inter-muscular coordination patterns compared to the pedal action of sprint cyclists (Koninckx, Leemputte, & Hespel, 2010). Therefore,
chronic exposure to different patterns of coordination, at the inter-muscular and kinematic level, could limit the transfer of increased neuromuscular strength to the competitive motor task and retard sports performance (Carroll, Riek, & Carson, 2001; Leirdal, Roeleveld, & Ettema, 2008; Romanazzi et al., 2015) and should be explored in future investigations aiming to quantify the movement specificity of training exercises.

2.2.5 Exercise Selection and Classification
As previously discussed, strength training means are widely employed in the programmes of elite and developmental athletes (Bolger, Lyons, Harrison, & Kenny, 2015). A problem that faces strength and conditioning practitioners is the selection of exercises to incorporate into the training programme, as there are a variety of mechanisms through which an individual can increase their neuromuscular potential to express task specific force (Cormie et al., 2011b). By acknowledging both the principles of overload and specify, the selection of exercises to include into an athletes training programme should reflect the desired neuromuscular adaptation, individual biological limitations to performance, and biomechanics of the competitive motor task in order for training to be most effective (Baker, 2014; McGuigan, 2014, Moir et al., 2018; Siff, 2003).

However, as recognised by Moir et al. (2018), often exercises are selected and categorised based solely on the principle of specificity, seeking to replicate the gross movement pattern and velocity of the competitive motor task. This perception of specificity was supported in the qualitative study by Burnie et al. (2017), who interviewed thirteen elite coaches across sprint disciplines in order to understand coaching philosophies surround the transfer of training to elite sports performance. Most coaches recognised the value of including traditional, maximal strength training (e.g. squats, deadlifts, leg press) for increasing motor potential, but classed these methods as non-specific and sought to add resistance to sporting movements (e.g. resisted sprinting) for specific training methods to encourage the transfer of training.

Further insight to elite coaching has revealed that the acquisition of a skill ‘mind set’ through tacit biomechanical knowledge of a competitive motor task (Irwin et al., 2005), and coaches perception of transfer (Bolger et al., 2016), influences the exercises coaches select for their athletes programmes. The importance of
increasing biomechanical understanding of the principles of training is therefore essential for evidence-based decisions within exercise selection.

Within the contemporary approach to exercise specificity based on replication of the competitive motor task, exercises are categorised on a spectrum of general (non-specific) to specific, with the most specific exercise being the competitive motor task itself (Baker, 1996; Bondarchuck, 2007; Moir et al., 2018; Rumpf et al., 2016; Wild et al., 2011; Young, 2006; Young et al., 2001). Within the British Athletics coaching literature (Crick, 2009), Bondarchuck’s (Bondarchuck, 2007) method of exercise classification has been adopted to facilitate exercise selection (Fig. 2.2).

Figure 2.2. Exercise classification hierarchy according to British Athletics coaching literature (Crick, 2009).
One of the major limitations within exercise selection for athletic performance is that the underlying research has often made recommendations on the effectiveness, or specificity of an exercise without quantifying the biomechanics of these exercises and comparing them to a competitive motor task (Crick, 2009; Baker, 1996; Wild et al., 2011; Young, 2006; Young et al., 2001). Instead, recommendations are often made based on contact times, visual assessment of postures, and movement velocity (Sheppard, 2003; Wild et al., 2011; Young et al., 2001).

Even though traditional maximum strength training against near maximal external loads is considered a ‘non-specific’ training method for sprinting, sprint coaches utilise these training exercises (Bolger et al., 2016) because of their ability to increase maximal muscular strength (Seitz et al., 2014). By determining an exercises level of specify based simply on replication of the competitive motor task, it devalues the efficacy of ‘non-specific’ training exercises that focus on stimulating biological adaptation (overload) to increase an athlete’s motor potential (Moir et al., 2018; Siff, 2003). This view also removes the term ‘specificity’ away from its origins, that recognise that specificity is an adaptive response to a biological stressor (Dick, 2002; Matveyev, 1981; Siff & Verkoshansky, 1999).

Based on the limitations of contemporary exercise selection frameworks, there is an argument for determining an exercises level of specificity based on stimulating relevant adaptations that target the biomechanical determinants of performance (Moir et al., 2018). However, currently there is a dearth of research providing underlying biomechanical knowledge to facilitate evidence-based decisions within exercise selection, leaving coaches to use the visual appearance of movement specificity to determine which exercises may transfer to enhanced sports performance (Bolger et al., 2016).

2.2.6 Training Methods to Enhance Sprint Performance
Throughout previous literature, various training methods have been shown to enhance a range sprint performance measures. A recent meta-analysis by Seitz et al. (2014) supported that increases in lower limb strength can positively transfer to increased sprint performance by finding a significant correlation ($r = -0.77$, $P < 0.05$) between effect sizes for improvement in squat strength and sprinting. However, Seitz et al. (2014) highlighted that strength improvements were not solely developed using traditional, non-ballistic heavy resistance exercises, but through combined
non-ballistic, ballistic (jump squats) and plyometric exercises. In support of combined training methods, Rumpf et al. (2016) concluded that joined ‘specific’ (sprint drills) and ‘non-specific’ (resistance and plyometric) training resulted in the greatest improvements in short (0 to 10 m) sprint distances. However, when considering longer sprint distances, resistance training was found to be less effective than simply engaging in sprinting itself (Rumpf et al., 2016).

Traditional non-ballistic exercises (Delecluse et al., 1995; Cormie, McGuigan, & Newton, 2010), ballistic exercises (Harris, Cronin, Hopkins, & Hansen, 2008; Cormie et al., 2010), Olympic weightlifting exercises (Tricoli, Lamas, Carnevale, & Ugrinowitsch, 2005) and plyometric exercises (Delecluse et al., 1995; Tricoli et al., 2005) have all been found to significantly improve measures of sprint performance (time or velocity) from 10-40 m. Conversely, other investigations have found that heavy strength exercises (Wilson, Newton, Murphy, & Humphries, 1993; Harris, Stone, O’Bryant, Proulx, & Johnson, 2000), ballistic exercises (Wilson et al., 1993; McBride et al., 2002) and plyometrics (Wilson et al., 1993) have not enhanced sprint performance from 5-30 m.

In the study by Blazevich and Jenkins (2002), 20 m sprint time in national level junior sprinters was shown to improve through strength training with high (4.3% improvement) and low (2.9% improvement) movement velocity. Furthermore, both groups also significantly increased 1RM squat strength (12.4 and 11.8%, respectively). Therefore, positive transfer of training was found for both groups, making it difficult to conclude which exercises were most effective. However, an eight week periodised high and low velocity training protocol was not shown to benefit 20 m sprint time in team sport athletes (Moir, Sanders, Button & Glaister, 2007). Whilst sample populations differed between groups, Blazevich and Jenkins (2002) permitted the continuation of sprint training alongside the interventions whilst Moir et al. (2007) did not, and could explain the differences in results. The efficacy of resisted sprint training to enhance performance above that of regular sprint training has also been inconclusive, with discrepancies in participants, apparatus and loading prescription confounding the results of these investigations (Petrakos, Morin, & Egan, 2016).

A limitation of much of the previous longitudinal evidence is that rarely have competitive sprinters been sampled. In the review article by Bolger, et al. (2015),
only five studies were identified that sampled competitive sprinters and presented outcome measures in the form of sprint time between 10-100 m. Overall, Bolger et al. (2015) supported the use of resistance training for enhancing sprint acceleration performance over 30 m distances. However, the variety of exercises implemented within the study make it difficult to elucidate the most effective methods. From the available evidence, it is unlikely that a single training method or exercise exists that can universally enhance sprint performance, and periodised approaches incorporating multiple training stimuli are therefore supported (Newton & Kraemer, 1994; Cormie et al., 2011b; Winkelman, 2009).

The efficacy of a mixed model approach likely reflects the different avenues to increase task specific expression of force (Cunanan et al., 2018), individual responses (Newton et al., 2002) and the complexity of maximal sprint running that elicits ever-changing technique as a race progresses (Nagahara, Matsubayashi, Matsuo, & Zushi, 2014). However, whilst the use of multiple training methods is supported (non-ballistic, ballistic, plyometric), coaches still face endless possibilities for the exact exercise to select within each category. By acknowledging the importance of both overload and specificity principles, the exercise type would be decided based on the desired biological adaptation (overload), with the final decision being made on similarity in movement pattern (specificity) that can facilitate the transfer of training (Young, 2006). Again, attention is brought to the lack of biomechanical interrogation of the principles of overload and specificity (Bolger et al., 2016), with further investigation required support objective decisions within exercise selection.

2.2.7 Biomechanical Analysis of Strength Training Exercises
Possessing a biomechanical understanding of a competitive motor task and training exercises is essential to ensure training is most relevant to the sport, and influences the way that coaches select training exercises (Burnie et al., 2017; Bolger et al., 2016; Irwin et al., 2005; Moir et al., 2018). A wealth of previous research has extensively investigated the biomechanics of various strength training exercises, offering coaches practical information to assist with exercise selection. For instance, empirical evidence has shown that performing deadlifts with a hexagonal bar compared to a conventional straight bar can elicit significantly increased 1RM strength, and peak force, velocity and power across submaximal loads (Swinton, Steward, Agouris, Keogh, & Lloyd, 2011). Other external kinetic studies have
identified increased RFD in the box squat compared with a traditional and powerlifting squat (Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012), increased peak power in the mid-thigh power clean compared with the push press and jump squat (Comfort et al., 2017), and increased external power during weighted jumps when the load is placed at arm’s length compared to across the shoulders (Swinton, Stewart, Lloyd, Agouris, & Keogh, 2012).

Extending beyond external kinetics, inverse dynamics analyses to calculate net joint moments and power have been conducted with deadlift variations (Swinton et al., 2011), squat variations (Swinton, Lloyd et al., 2012), and the anterior lunge (Riemann, Lapinski, Smith, & Davis, 2012). When examining the power clean exercise across different external loads (65%, 75%, 85% 1RM), responses have been found to be joint and variable specific, with peak moment, power and rate of torque development showing different responses within and between the ankle, knee and hip joints (Kipp, Redden, Harris, & Sabick, 2011). Similar observations have been made in the jump squat exercise, with lower limb joint powers shown to reach their peak magnitude at different external loads (Farris, Lichtwark, Brown & Cresswell, 2016; Jandacka, Uchytíl, Farana, Zahradník, & Hamill, 2014; Moir, Gollie, Davis, Guers, & Witmer, 2012). Joint kinetic analyses have also been conducted when towing weighted sleds with an additional load of 50% body mass, showing that attaching the external load to the shoulder or waist shifts the extensor moment demand towards the knee and hip, respectively (Lawrence, Hartigan, & Tu, 2013).

Overall, the evidence from the aforementioned biomechanical investigations can offer practitioners biomechanical insight into commonly prescribed training exercises, providing empirical evidence to bring objectivity to exercise selection. However, the exact characteristics of overload and / or specificity can only be quantified when the biomechanics of a training exercise are evaluated against a competitive motor task. These types of investigations are more limited within the sports biomechanics literature, especially with attention to joint kinetics and intra-limb coordination during sprinting.

With regard to sprinting, previous investigations have evaluated the specificity of plyometric exercises for enhancing maximal velocity sprinting (Mero & Komi, 1994), and a range of strength training exercises for enhancing the block start (Okkonen & Hakkinen, 2013). In both studies, external force and electromyography (EMG) were
used to quantify the overload and specificity characteristics of the studied exercises, although Okkonen and Hakkinen (2013) also measured joint kinematics to investigate the specificity of movement patterns. In the earlier study, Mero and Komi (1994) selected plyometric exercises that were intended to replicate maximal velocity sprinting and results showed no differences in EMG patterns across all tasks. However, maximal stepping and hopping exercises were found to exhibit 1.64 to 1.93 and 1.54 to 1.82 times greater vertical and propulsive forces compared to maximal sprinting. The authors therefore concluded that whilst all exercises were sprint specific (based on similar EMG) the stepping and hopping exercises could provide additional benefit due to the opportunity for them to increase the ability to produce force (Mero & Komi, 1994).

Whilst Mero and Komi (1994) demonstrated a multidimensional approach to quantifying overload and specificity, the exercises selected were intended to replicate maximal velocity sprinting. Conversely, in the strength and conditioning community, the challenge is to understand the transfer of exercises that are not intended to replicate the outward appearance of a competitive motor task (Burnie et al., 2017; Siff, 2003; Stone & Stone, 2011). This was addressed in the study by Okkonen and Hakkinen (2013), who evaluated a range of strength training exercises with the block start action, including loaded half squats with maximum and 70% 1RM load, loaded and unloaded countermovement jumps, and resisted sled pulls. Results showed that the half squat exercises were most effective at overloading the external force requirement of the block start, and also elicited the greatest magnitude of gluteus maximus activation. However, the efficacy of the half squat to transfer to increased block start performance was questioned by the lack of similarity with respect to joint angular displacement and velocity, in which the countermovement jump and sled pulls showed greater correspondence to the block start. The exercises with greater specificity with respect to movement pattern and velocity were concluded to have the greatest potential to transfer, although there was no established overload stimulus (Okkonen & Hakkinen, 2013).

Once more, the approach by Okkonen and Hakkinen (2013) confirms contemporary approaches to determining an exercises level of specificity based on global measures of movement pattern, failing to acknowledge movement from an intra-limb coordination perspective. In addition, Okkonen and Hakkinen (2013) was limited by the absence of mechanistic explanation for how exercises that do not
replicate a competitive motor task may still serve to enhance performance by targeting the biomechanical determinants of performance (Moir et al., 2018).

A major limitation of the previous two studies is the lack of joint kinetic information that can provide more detailed understanding of the nature of overload at the level of the joints, which are responsible for the external kinetics often reported (Winter, 2009). Although not conducted within sprinting, a joint level approach featured in a series of investigations into the specificity of progression exercises for the gymnastics long swing, evaluating single joint kinematics (Irwin & Kerwin, 2005), inter-joint coordination (Irwin & Kerwin, 2007a), and joint kinetics (Irwin & Kerwin, 2007b). During these investigations, the authors established a ranking system based on the similarity of the progressions against the competitive motor task, using route mean squared differences (Irwin & Kerwin, 2005; 2007a; 2007b). The outcome of these studies informed skill selection from a multidimensional approach to understanding the biomechanics of specificity. However, the ranking system used by Irwin & Kerwin (2005; 2007a; 2007b) only considered similarity with a competitive motor task, and not the requirement for overload to stimulate biological adaptation.

The complexity when balancing the principles of overload and specificity for exercise selection were identified in the study by MacKenzie, Lavers, and Wallace (2014), considering external force, joint kinematics and electromyography in a sample of 20 male and female team sport athletes during the power clean and jump squat exercise in comparison to a countermovement jump. Results highlighted that the power clean elicited the greatest overload in peak force and RFD, but the jump squat demonstrated greater similarity in joint angular displacements and muscle activation. The authors suggested that based on similarity, the jump squat should be the better exercise at increasing countermovement jump performance. However, the notable overload in peak force and RFD from the power clean suggested that exercise selection should also consider the specific neuromuscular ability to be trained, and not be entirely based on replication of the competitive motor task (MacKenzie et al., 2014).

The requirement for both overload and specificity when evaluating the potential for an exercise to elicit increases in sports performance was again considered in the study by Irwin et al. (2007), benefitting from a joint kinematic and kinetic approach to evaluate the power clean as a sprint specific exercise. In their study, Irwin et al.
(2007) established increased kinetic demand at the hip joint during the power clean compared with sprint stance phases at approximately 5 and 15 m, suggesting that the power clean provided an overload stimulus that could facilitate increased ability of the hip extensors to generate power. However, when qualitatively assessing hip power against joint angle, differences were noted in the joint angle at which peak power occurred in the power clean and sprint stances, indicating that increases in hip extensor power may have limited potential to transfer to sprinting. To the author’s knowledge, Irwin et al. (2007) is the only study to analyse joint kinematics and kinetics simultaneously in this context, recognising the importance of both overload and specificity at the musculoskeletal level to inform decisions within exercise selection to enhance sports performance. However, whilst novel in approach, further research is required to examine musculoskeletal demand for other lower limb joints, whilst concomitantly examining characteristics of intra-limb coordination. In addition, considering a more extensive range of strength training exercises would allow future investigations to interrogate the principles of overload and specificity for exercise selection in more detail, providing wider application to an athletes’ periodised training cycle (Cormie et al., 2011b; Moir et al., 2018; Winkelman, 2009; Young, 2006).

By considering the available literature, there is a clear dearth of research that has taken a holistic, joint level approach to understand the principles of overload and specificity within exercise selection. Future studies should attempt to evaluate single joint kinematics and kinetics in order to gain insight towards the specific nature of neuromuscular-skeletal adaptation, alongside intra-limb coordination to infer movement specificity that can facilitate the positive transfer of increased neuromuscular potential into performance enhancements. In order for this to occur, a competitive motor task is required that exhibits characteristics consistent with the aims of strength training.
2.3 The Competitive Motor Task: Block Start in Athletic Sprinting

The block start, referred to as the time when a sprinter pushes against the blocks following the starting signal (Mero, Komi, & Gregor, 1992), is a sporting skill that requires the generation of large external force, in minimal time, oriented in the running direction (Baumann, 1976; Mero, Luhtanen, & Komi, 1983; Willwacher et al., 2016). Therefore, the role of neuromuscular strength is critical to the starting action (Mann, 2007), and is synonymous with the purpose of strength training to enhance task specific force production (Siff, 2003).

As well as being aligned with the aims of strength training, the block start holds relevance to the outcome of short sprint races (60 m and 100 m events), as an athlete attempts to maximise centre of mass acceleration from the stationary ‘set’ position. Despite the fact that the block phase (including reaction time) only comprises about 5% of total 100 m race duration (Tellez & Doolittle, 1984), over one third of maximal horizontal velocity can be achieved at block exit (Harland & Steele, 1997). As a result, centre of mass (CM) acceleration is greatest during this phase of a sprint race (Willwacher et al., 2016). Recently, the ability to accelerate and achieve higher velocity over 40 m was shown to discriminate between elite and sub-elite sprinters (Rabita et al., 2015), supporting that the optimal performance strategy in the short sprint events is one that minimises the time spent running at submaximal velocity (van Ingen Schenau et al., 1994).

Horizontal acceleration of the CM is determined by the propulsive forces generated by the sprinter in the blocks, and when accompanied with displacement of the CM, work is performed in the running direction. The rate at which this work is achieved is equal to average horizontal power, which when normalised to body mass and leg length (NAHP) has been identified as the best descriptor of starting block performance (Bezodis et al., 2010). Although the importance of the block start is implied through its importance for generating sprint velocity, NAHP (using body height instead of leg length) has been evidenced to account for 42% of the variance in 100 m personal best (PB) time, in a large sample of 154 sprinters with PB’s ranging from 9.58 to 14.00 seconds (Willwacher et al., 2016).

The link between block start performance and adaptations to strength training, alongside its importance to race outcome (Willwacher et al., 2016), make the block start a valid and meaningful competitive motor task to investigate in the current
research. Section 2.3 will continue to discuss the available literature investigating the biomechanics of block start technique.

2.3.1 Biomechanics of the Block Start
2.3.1.1 Quantifying Block Start Performance

Success in all sprint events is founded on the ability to cover a set distance in the least possible time. However, when considering a discrete part of a sprint race, such as the block start, defining successful performance is not as clear (Bezodis et al., 2010). Previous research has adopted many ways of quantifying sprint start performance, such as the time spent in the blocks (Dickinson, 1934), the time taken to reach a specific distance (Henry, 1952; McClements, Sanders, & Gander, 1996; Mendoza & Schollhorn, 1993; Mero et al., 1983), or average velocity over a given distance (Schot & Knutzen, 1992). However, the most commonly used measure of performance in historical literature has been the horizontal velocity of the centre of mass at block exit (Baumann, 1976; Henry, 1952; Mendoza & Schollhorn, 1993; Mero et al., 1983; Mero, 1988; Mero & Komi, 1990; Guissard, Duchateau, & Hainaut, 1992). Some studies extended beyond block exit velocity to report average acceleration (e.g. Baumann, 1976), or average power (Mendoza & Schollhorn, 1993; Mero et al., 1983), which introduced conflict in the measures by which block start performance were being quantified.

As the aim of a sprint is to perform a specific amount of horizontal work (translate CM over a given distance) in the shortest amount of time, the ability to produce average horizontal power (the rate of doing work) has surfaced as the best descriptor of block start performance (Bezodis et al., 2010). To discern the best method of block start performance, Bezodis et al. (2010) conducted an investigation by which ten performance measures were obtained from 12 university level sprinters (100 m PB = 11.30 ± 0.42 s) performing maximal 30 m sprints from blocks. Spearman rank order correlations showed disagreement in rank order for each of the 10 performance measures, highlighting that the selected measure of performance can influence conclusions and should be considered when addressing the literature.

The authors of Bezodis et al. (2010) were to conclude that average external horizontal power normalised to body mass and leg length (NAHP) was the most appropriate measure of block performance, as it reflected the rate at which required
horizontal work is performed, whilst accounting for variations in morphology (Bezodis et al., 2010). Subsequent investigations have successfully utilised NAHP (Bezodis, Salo, & Trewartha, 2014; Bezodis et al., 2015), sometimes using different normalisation procedures (Willwacher, Herrmann, et al., 2013; Willwacher et al., 2016) to understand the determinants of block start and early sprint acceleration performance.

2.3.1.2 Set Position
Many studies have investigated body configuration in the set position (Atwater, 1982; Bezodis et al., 2014; Borzov, 1978; Mero et al., 1983; Mero, 1988; Mero & Komi, 1990; Slawinski, Bonnefoy, Leveque, et al., 2010). From these investigations, a range of lower limb joint angles have been reported for the ankle (front, 94°-107°; rear, 99°-111°), knee (front, 89°-11°; rear, 117°-136°) and hip (front, 41°-52°; rear, 75°-89°), in sprinters with 100 m personal best times ranging from 9.98 s to 11.85 s. Whilst faster sprinters have been found to exhibit greater hip flexion (Mero et al., 1983) and a more extended rear knee angle (Slawinski, Bonnefoy, Leveque, et al., 2010), other work has demonstrated that differences in set position cannot discriminate between levels of block performance (Bezodis et al., 2015). In addition, large standard deviations in set position kinematics have been reported in all the aforementioned studies, suggesting that even in homogenous groups there is large variability, making it difficult to conclude an 'optimal' set position.

The pose an athlete adopts during 'set' can be influenced by adjusting the starting block positions, most namely the spacing (distance between front and rear blocks) and obliquity (angle of each block relative to the running direction) (Harland, & Steele, 1997). There are three types of block spacing often described in the literature: bunched (<30 cm), medium (30-50 cm) and elongated (>50 cm) (Harland & Steele, 1997). Early research focused on block spacing has been conflicting, with the bunched start found to increase time to 2.5 m (Dickinson, 1934) and reduce block time (Henry, 1952). Furthermore, elongated spacing has been found to increase force production (Kistler, 1934) and medium spacing shown to reduce sprint time between ~ 15 and 50 m (Henry, 1952; Stock, 1962). More recently, an elongated spacing has been shown to increase the magnitude of horizontal velocity achieved at block exit (Slawinski et al., 2012) through an increased push duration (Slawinski et al., 2012; 2013). Whilst increasing horizontal velocity might appear to benefit the attainment of high sprint velocities, the increased time taken to achieve
this velocity goes against the 'least possible time' nature of sprinting and may have negatively affected average horizontal power (Bezodis et al., 2010). In addition, Slawinski et al. (2013) concluded that a medium block spacing could be the best compromise between the conflicting nature of minimising block time and maximising velocity, whilst achieving balance in the organisation of upper and lower limb joint velocities.

Reducing block obliquity between 70°, 50° and 30° has been shown to increase the horizontal velocity achieved at the end of the block phase, without changing block time and therefore leading to increased average acceleration (Guissard et al., 1992). The authors observed that with reduced block obliquity, the soleus and gastrocnemius muscles were positioned at greater length in the set position, reaching maximal length sooner in the starting action leading to a longer relative duration of shortening. Furthermore, increases in gastrocnemius activation were observed at 30° block obliquity, leading to increased stiffens of the ankle complex, assisting force transmission into the blocks (Cavagna, 1977). The observed neural and mechanical changes that contributed to increased block velocity without an increase in push duration, appeared to be the mechanisms through which sprinters were better able to accelerate from the starting blocks (Guissard et al., 1992).

Years later, Mero et al. (2006) found that horizontal velocity at block exit was significantly increased when adopting 40° (3.39 ± 0.23 m.s\(^{-1}\)) block obliquity compared with 65° (3.30 ± 0.21 m.s\(^{-1}\)). Total block time was found to be similar between conditions, although an increased rear block time in the 40° condition (0.188 ± 0.008 vs. 0.172 ± 0.015 s) lead to significantly greater rear block impulse (96.4 ± 13.8 vs. 82.3 ± 20.1 Ns) and the observed changes in block exit velocity (Mero et al., 2006). Again, the authors explained this increase in block exit velocity through longer initial muscle-tendon lengths of the gastrocnemius and soleus at the onset of force production, contributing to increased peak ankle joint moment and subsequent power generation during muscle shortening (Mero et al., 2006).

Although the aforementioned empirical evidence can be used to suggest the optimal block configuration with respect to spacing and obliquity, there is no biomechanical ‘best practice’ and in practice, block settings are typically based on the athlete’s or coach’s preference (Taboga, Grabowski, Prampero, & Kram, 2014).
2.3.1.3 External Kinematics & Kinetics

Understanding the force applied to the starting blocks has been a topic of interest since the 1930’s. One of the earliest measurements of starting block forces were conducted at the University of Iowa (Kistler, 1934) by which normal starting blocks were attached onto two individual spring scales which were sunk below the track surface. Later, Henry (1952) used a rack and pinion arrangement to measure horizontal forces during the starting action.

Since this pioneering study work, various methods of measuring starting block forces have been documented, including the attachment of industry standard starting blocks onto force platforms (Baumann, 1976; Cousins & Dyson, 2004; Mendoza & Schollhorn, 1993; Mero et al., 1983; Mero et al., 1988; Otsuka et al., 2014; Otsuka, Kurihara, & Isaka, 2015; Schot & Knudsen, 1992; Taboga et al., 2014), or by constructing force-instrumented starting blocks (Fortier et al., 2005; Guissard et al., 1992; Lemaire & Robertson, 1990; McClements et al., 1996). From these investigations, observed values of block time have been shown between 0.32 to 0.36 s, with the rear leg in contact between 44% and 55% of total block time (Bezodis et al., 2015; Harland, & Steele, 1997; Mero, & Komi, 1990). In addition, for male sprinters able to complete the 100 m in less than 11 seconds, block exit velocities up to 4 m.s\(^{-1}\) have been observed, leading to average acceleration of up to 12 m.s\(^{-2}\) (Baumann, 1976; Fortier et al., 2005; Mero & Komi, 1990; Mero et al., 1988; Otsuka et al., 2014).

One of the earliest studies to investigate the differences in block start kinetics between different levels of sprint ability was conducted by Baumann (1976), who divided 30 male sprinters into three groups based on 100 m PB time. The fastest group (100 m PB = 10.35 ± 0.12 s) was observed to generate greater horizontal impulse compared with the intermediate (11.11 ± 0.16 s) and slow groups (11.85 ± 0.24 s), despite spending the same amount of time in the blocks as the intermediate group (0.37 s), and less time than the slowest group (0.39 s). The increased block velocity, as a result of the larger impulses, was thus concluded to be a result of greater force production not increased block time (Baumann, 1976).

A few years later, Mero et al. (1983) supported the results of Baumann (1976) by confirming that higher block velocities were achieved through greater horizontal force production and not elongated block time. It was therefore apparent from as
early as the 1970’s, that the ability to generate high magnitudes of horizontal force was a key characteristic of successful block performance (Baumann, 1976; Mero et al., 1983).

Since these early investigations, subsequent empirical evidence has identified several key external kinetic variables separating different levels of sprint ability. Some of these have included greater front and rear block rate of resultant force development (Willwacher, Herrmann, et al., 2013), greater rear block peak resultant force (Fortier et al., 2005) and more balanced front and rear peak resultant forces (Willwacher, Herrmann, et al., 2013). However, Otsuka et al., (2014) were unable to detect differences in average resultant force between well trained (100 m PB = 10.87 ± 0.41 s) and trained (11.31 ± 0.42 s) sprinters. In addition, Otsuka et al. (2014) observed no significant differences in front (6.70 ± 0.58 N.kg\(^{-1}\) vs. 5.99 ± 0.67 N.kg\(^{-1}\)) or rear (5.82 ± 0.71 N.kg\(^{-1}\) vs. 5.41 ± 0.88 N.kg\(^{-1}\)) average horizontal force between their well trained and trained groups, respectively, although significantly greater total average horizontal force was observed (9.72 ± 0.36 N.kg\(^{-1}\) vs. 8.41 ± 0.49 N.kg\(^{-1}\)).

By demonstrating increased total average horizontal force without increases in total average resultant force, Otsuka et al. (2014) concluded that a trait of faster sprinters was a greater ability to orientate the total resultant force vector in the running direction. The ability to more effectively orientate the resultant force vector in the horizontal direction was later supported by Rabita et al. (2015) as a characteristic of superior 40 m sprint performance, when comparing elite (100 m PB = 9.95 to 10.29 s) and sub elite (100 m PB = 10.40 to 10.60 s) sprinters.

Interpreting the relative importance of external force applied to the front and rear block towards overall block performance from the aforementioned studies can be difficult. The inconsistency between studies may be accounted for by the different athletes used, different statistical analyses, or that between-group analyses have often not been based on block performance alone, but overall sprint performance. Therefore, insights have been provided towards understanding how better sprinters produce force in the block start, but little evidence has elucidated the key external kinetic determinants of block start performance by itself.

The external kinetic determinants of starting block performance, explicitly, was addressed in detail in a recent comprehensive investigation by Willwacher et al.
In their study, pioneered by the German Sport University in Cologne, bespoke piezoelectric starting blocks were engineered to obtain 3D force data from different training groups across the world, resulting in a large sample of 154 sprinters. Participants of the study by Willwacher et al. (2016) were both male (n = 103) and female (n = 51) with 100 m performances ranging from the fastest recorded time in history (9.58 s) to 14.00 s. Their large sample size permitted more sophisticated statistical analyses to understand the key external kinetic determinants of starting block performance, in which exploratory factor analysis and multiple regression were used to extend beyond bivariate correlations or between-group analyses.

From their analysis, 86% of the variance in block performance (NAHP using height instead of leg length) was explained by the magnitude of force applied to both blocks, and the horizontal orientation of these forces. Exploration of individual regression coefficients suggested that maximising rear block resultant force was more important than ensuring its orientation in the running direction, although both magnitude and orientation were of similar importance in the front block. However, the results of Willwacher et al. (2016) ultimately concluded that high average horizontal force must be applied to the front and rear block in order to maximise block start performance.

Whilst the majority of studies have only considered force at the foot-block interface, other work has analysed the contribution of force applied through the hands into the ground on block start performance, through multiple force platforms systems enabling forces to be measured from all four contact points (Graham-Smith, Natera, & Saunders, 2014; Otsuka et al., 2014). The results of both investigations agreed that the arms contribute towards vertical impulse production and contribute a braking impulse opposite in direction to that produced by the legs. In the study by Graham-Smith et al. (2014) a case study approach of one elite student athlete (100 m PB = 10.51) revealed that the arms contributed 18% to the total vertical impulse during the block start and -2.4% to horizontal impulse. The resulting influence on block exit velocity was a reduction when including hand forces from 3.50 to 3.45 m.s\(^{-1}\) (Graham-Smith et al., 2014).

Whilst Otsuka et al. (2014) confirmed the braking impulse produced by the hands across three groups of sprinters (-0.002 ± 0.009 to -0.023 ± 0.017 Ns.kg\(^{-1}\)), their
results were unable to conclude that reducing braking impulse contributed to greater block performance. Instead, the role of force production through the hands in the block start was theorised to preserve whole body balance, allowing the sprinter to adopt a more forwards position and facilitate horizontal orientation of external force applied directly to the blocks (Otsuka et al., 2014).

It is therefore apparent that the hands produce vertical force during the block start that is not negligible (Graham-Smith et al., 2014; Otsuka et al., 2014). However, hand forces do not appear to discriminate between different performance levels and may be influenced by the set position adopted, which is known to be individual dependent (Bezodis et al., 2015; Taboga et al., 2014). Propulsive forces are applied to the starting blocks (Graham-Smith et al., 2014; Otsuka et al., 2014) through muscle contraction of the lower limb (Guissard et al., 1992; Mero et al., 2006; Willwacher et al., 2016). Consequently, empirical research has sought to investigate lower limb biomechanics to understand block start technique.

2.3.1.4 Joint Kinematics

Despite a wealth of research regarding kinematics and kinetics of the centre of mass, and set position joint angles, there have been less empirical studies concerned with joint kinematics during the block start to help describe technical strategies during this task. Joint angular displacements were detailed in the study by Bezodis et al. (2015), who observed greater extension range of motion at the front leg ankle (36 ± 10° vs. 19 ± 9°) knee (73 ± 7° vs. 18 ± 6°) and hip (113 ± 9° vs. 31 ± 13°) joint compared with the rear leg. Further correlational analysis revealed that rear hip extension range of motion and front and rear hip peak extension angular velocity were moderately correlated with block performance (all r-values = 0.49), and identified the importance of the hip joint mechanics towards block start NAHP (Bezodis et al., 2015).

Through investigation of sagittal plane joint kinematics, the global movement of the lower limb joints have been described (Bezodis et al., 2015; Slawinski, Bonnefoy, Ontanon, et al., 2010). In both the front and rear leg, the ankle joint has shown to undergo a dorsiflexion-plantarflexion pattern, whilst both hip joints have been found to extend throughout the majority of the time each leg is spent in contact with their respective block (Bezodis et al., 2015). Knee joint motion in the front leg has been shown to remain relatively still during the first half of the block phase, before
undergoing extension prior to block exit (Bezodis et al., 2015). These general joint kinematic patterns are in agreement with those observed throughout sprint acceleration (Bezodis et al., 2014; Charalambous et al., 2012; Debaere et al., 2013), and provides evidence to support the emergence of a rotation-extension strategy in the block start that is consistent with accelerating over ground (Jacobs & van Ingen Schenau, 1992).

Both Bezodis et al. (2015) and Slawinski, Bonnefoy, Ontanon, et al. (2010) were able to identify a proximal-distal timing of peak extension angular velocities at the front leg, consistent with other stance phases during sprint acceleration (Bezodis et al., 2014; Charalambous, Irwin, Bezodis, & Kerwin, 2012; Debaere, Delecluse, Aerenhouts, Hagman, & Jonkers, 2013; Hunter, Marshall, & McNair, 2004b; Jacobs & van Ingen Schenau, 1992). However, a proximal-distal strategy of peak extension joint angular velocities was not observed at the rear leg in the block start, caused by an extension-flexion action of the rear knee joint (Bezodis et al., 2015; Slawinski, Bonnefoy, Ontanon, et al., 2010). This kinematic asymmetry between the front and rear leg is more prominent than that of the ankle and hip joint, which is theorised to be a result of the rear knee joint being placed in greater extension in the set position, limiting its extensor range of motion (Bezodis et al., 2015).

2.3.1.5 Joint Kinetics
Although external kinetic analyses provide valuable insight to the resulting force applied to the blocks that translate the CM, and joint kinematic analyses describe joint motion observed, analysing lower limb joint kinetics allows for an increased understanding of the causes of segment motion that are responsible for CM acceleration (Winter, 2009). Joint kinetic analyses of sprinting have often been conducted and have provided valuable insight towards the musculoskeletal demand of sprinting (Bezodis, Kerwin, & Salo, 2008; Bezodis et al., 2014; Charalambous et al., 2012; Debaere et al., 2013; Exell, Irwin, Gittoes, & Kerwin, 2012; Johnson & Buckley, 2001). An understanding of musculoskeletal demand is not only important to comprehensively understand the biomechanics of a given task, but also valuable when seeking to understand how a training exercise may overload the musculoskeletal system to facilitate biological adaptation (Irwin & Kerwin, 2007b; Irwin et al., 2007).
To the author’s knowledge, only two previous studies have determined lower limb joint kinetics during the block start. The first of which was conducted by Mero et al. (2006), who calculated joint moment and power data for nine male sprinters (100 m PB = 10.86 ± 0.34 s) by combining force and 2D video analysis and assigning the centre of pressure (COP) to the metatarsophalangeal joint. Explicit magnitudes of joint moment and power were not provided in the study by Mero et al. (2006), although general patterns could be inferred. Joint moments at the front and rear ankle joints were shown to be extensor throughout, leading to an initial period of extensor power absorption followed by generation as the ankle underwent a flexion-extension sequence, a common feature observed during sprint acceleration (Bezodis et al., 2014; Braunstein et al., 2013). Extensor moment and power generation was also observed at both hip joints, however notable differences in joint kinetic patterns were observed at the knee joint, with small magnitudes of moment and power found at the rear leg (Mero et al., 2006).

More recently, utilising 3D motion capture and force platforms, hip joint kinetic data were presented by Otsuka et al. (2015) whilst investigating the effect of stance width on block start performance (NAHP) in a sample of 14 male sprinters (100 m PB = 10.99 ± 0.40). Resultant joint moment and power at the hip joint were calculated through standard inverse dynamics procedure (Winter, 2009), although estimation of the COP was not defined. Again, discrete measures of kinetic data were not provided, although graphical representation of joint moment and power were in agreement with the temporal nature shown in Mero et al. (2006).

2.3.1.6 Electromyography (EMG)

Few studies have utilised EMG to measure and understand muscle activity during the block start (Coh, Peharec, & Bacic, 2007; Guissard & Duchateau, 1990; Mero & Komi, 1990). Both Mero and Komi (1990) and Coh et al. (2007) observed that the gluteus maximus of the rear leg was the first muscle to activate during the block phase. In the absence of gluteus maximus data, Guissard and Duchateau (1990) observed the biceps femoris was the first muscle to activate, indicating the hip extensors initiate leg extension during the block start. At the rear leg, subsequent activation of the quadriceps muscles followed by the soleus and gastrocnemius were observed, although the quadriceps were only activated during the beginning of the rear leg phase (Coh et al., 2007; Guissard & Duchateau, 1990). This deactivation of the quadriceps is in agreement with low moment and power data at
the rear leg (Mero et al., 2006) and may indicate different functional roles of the rear and front knee extensors during the block start. At the front leg, quadriceps (vastii) activation begins soon after that of the hip extensors (Coh et al., 2007; Guissard & Duchateau, 1990). However, rectus femoris activation is delayed towards the end of the block phase, potentially due to its biarticular nature inhibiting hip extension at the beginning of the block start (Guissard & Duchateau, 1990). In both legs, initial soleus and gastrocnemius activation occurred concomitantly with ankle dorsiflexion, indicating that these muscles were initially contracting under eccentric conditions, indicative of a stretch-shortening action of the plantarflexors (Guissard & Duchateau, 1990; Mero & Komi, 1990; Mero et al., 2006).

2.3.1.7 Section Summary
Assessing previous literature concerned with biomechanics of the block start, it is evident that comprehensive analysis of lower limb joint kinetics is missing. Undertaking a detailed analysis of lower-limb joint kinetics would provide biomechanists and practitioners with a greater understanding of the musculoskeletal demand of executing the block start, which could influence the assessment and selection of appropriate training exercises. In addition, future research should seek to understand the relationships between lower limb joint kinetics, external kinetics and overall performance (NAHP) to increase conceptual understanding of successful block start performance.

So far, theories of strength training and the biomechanics of block start technique have been discussed in detail. In recent years, sports biomechanics research has begun to acknowledge dynamical systems theory of human movement, understanding that movement unlikely arises from a central governing programme (Schmidt, 1975), but through a process of self-organisation through interacting constraints on action (Newell, 1986). The theoretical background of dynamical systems theory, its central concepts of movement coordination and variability, and the relevance of dynamical systems to training theory will now be discussed.
2.4 Dynamical Systems Theory of Motor Control

Dynamical systems theory has grown from advancements in understanding complex systems in physics and mathematics, describing the evolution of a system over time (Thelan & Smith, 1998). Within the context of human movement, the human body can be viewed as a complex biological system, comprising nearly 800 muscles and 100 joints. This complex system provides an abundance in degrees of freedom to accomplish any given motor task (Bernstein, 1967; Kelso et al., 1981; Vereijken, & van Emmerik, 1992). Dynamical systems theory has therefore provided a theoretical framework for scientists to understand the organisation of movement, examining human movement as an emergent process based on the intentions of the performer and interaction between the biological system and the constraints imposed on the system (Kugler, Kelso, & Turvey, 1982; Newell, 1986).

The transition towards dynamical systems theory was stimulated by the degrees of freedom problem, pioneered by Russian movement scientist Nicolai Bernstein (Bernstein, 1967). Bernstein proposed that a key problem for human movement scientists was to understand the emergence of coordinated movement form a complex biological system with redundant biomechanical degrees of freedom. Bernstein famously defined coordination as ‘the process of mastering redundant degrees of freedom’ (Bernstein, 1967). By managing redundant degrees of freedom, the many components of the complex biological system (joints, segments, muscles and motor units) can be brought into relation to form stable movement patterns, or coordinative structures (Kugler et al., 1980; Turvey, 1990). Coordinative structure theory (Kugler et al., 1980; 1982) proposes that coordination emerges as a consequence of the constraints imposed on the biological system, with the resulting pattern of coordination reflecting the self-organisation of the biological system.

Newell (1986) extended initial theorising of constraints on action and outlined a model in which three categories of constraints interact to guide the self-organisation of emergent coordination patterns. Newell (1986) defined the constraints on action as internal or external boundaries or features that shape the organisation of emergent coordination patterns, eliminating certain configurations and reducing the biomechanical degrees of freedom. In Newell’s model of constraints on action (Newell, 1986), three categories of constraints have been proposed, which interact to determine the emergent coordination patterns to satisfy the task demands: the organism, the environment and the task (Fig. 2.3).
Properties embedded within the individual, such as their physiological, cognitive, psychological and emotional attributes form the organismic constraints to action (Newell, 1986). Perhaps the most influential organismic constraint that can shape movement coordination is the intentions of the individual (Kelso, 1995). In the world of elite sport, neuromuscular-skeletal constraints are of particular interest when seeking strategies to maximise human performance in the most effective and efficient manner.

Environmental constraints are recognised as those that are external to the organism (Newell, 1986), including the physical environment (e.g. temperature) or interaction with equipment or apparatus. Task constraints involve the goal of the motor task itself. In a number of closed sporting tasks (e.g. gymnastics), the rules of the event specify a desired pattern of coordination. However, in more open tasks, the goal of the task merely constrains the range of coordination patterns that can be produced in the pursuit of achievement, without dictating an optimal pattern of coordination (Newell, 1986). Interaction between all constraints ultimately govern the self-organisation of coordinated movement (Fig. 2.3).
Dynamical systems theory underpins the emergence of motor behaviour within the constraints imposed to action, suggesting that coordination emerges from the interaction of the components of a complex biological system without explicit instructions arising from the organism itself (Kugler et al., 1980; Haken, Kelso, & Bunz, 1985). Fundamental experiments examining the relative phase between index fingers by Kelso (Kelso, 1981; 1984) has pioneered understanding of movement organisation, stability and change, identifying abrupt changes in coordination at critical frequencies of oscillation. This transition, known as a phase transition, was characterised by an increase in coordination variability (or loss of stability) of the two fingers prior to the phase transition. The non-linearity in the phase transition was identified, as when the oscillation frequency was reduced below the critical threshold, no change in coordination was observed, a phenomenon known as hysteresis (van Emmerik & van Wegen, 2000).

A theoretical model was later developed by Haken et al. (1985) based on the findings of Kelso (1981; 1984). Central to this model was the idea that coordination variability is essential for changes in coordination pattern (or phase transitions), and this loss of stability (increased variability) occurs at critical values of an order parameter (e.g. oscillation frequency). From the empirical evidence provided by Kelso (1981; 1984) and Haken et al. (1985), it became clear that movement variability could be a functional entity that facilitates that discovery and adoption of stable coordination states in response to changing constraints on action.

Subsequent research has supported the observation of increased coordination variability prior to phase transitions, in the context of walking at different speeds (van Emmerik & Wagenaar, 1996) and during the transition from walking to running (Diedrich & Warren, 1995). It should be acknowledged that not all research has supported this concept, demonstrating during gait that variability does not increase around the walk to run transition (Seay, van Emmerik, & Hamill, 2006) and that variability and stability are independent features of movement dynamics (Li, Haddad, & Hamill, 2005).

However, many previous investigations have highlighted that increases in coordination variability can be revealing of an impending abrupt change in the biological system (Haken et al., 1985; Hamill et al., 1999). Examples have included increases in intra-limb (inter-segmental or inter-joint) coordination variability demonstrated at joint motion reversal (Heiderscheit, Hamill, & van Emmerik, 2002;
Ghez & Sainburg, 1995; Needham, Naemi, & Chockalingam, 2014), the onset of movement (Wilson, Perkin, McGuigan, & Stokes, 2016), and the termination of stance (Hamill et al., 1999; Awai & Curt, 2014). These findings have supported that increased coordination variability can indicate abrupt changes in the state of the system, which has been theorised to be a result of the increased neuromuscular complexity at these transition points (Heiderscheit, 2000).

2.4.1 Measuring Coordination & Coordination Variability
The assessment of coordination is fundamental to dynamical systems investigations, featuring within clinical and sporting environments to provide a measure of the relative motion between components within a functionally linked system (Sparrow, Donovan, van Emmerik, & Barry, 1987). Often, coordination is inferred through the concept of kinematic coupling, meaning the interaction between segments or joints (Hamill, Palmer, & van Emmerik, 2012). Intra-limb coordination therefore reflects the coupling between segments (inter-segmental, Hamill et al., 1999) or joints (inter-joint, Heiderscheit et al., 2002) of the same limb and both represent the movement coordination between two biological oscillators (Hamill et al., 2000).

Intra-limb coordination measures have often been applied to quantify coordination during locomotive tasks, ranging from walking (Chang, van Emmerik, & Hamill, 2008; Needham et al., 2014; van Emmerik & Wagenaar, 1996), to running (Hamill et al., 1999; Heiderscheit, 2002), and maximal velocity sprinting (Gittoes & Wilson, 2010). Coordination analyses have also been applied to understand movement organisation in other sporting tasks, such as pistol shooting (Scholz, Shoner, & Latash, 2000), instep soccer kicks (Li, Alexander, Glzaebrook, & Leiter, 2016), karate kicking (Quinzi, Sbriccoli, Alderson, Di Mario, & Camomilla, 2013), triple jump (Wilson et al., 2008), gymnastics long swing (Irwin & Kerwin, 2007a), and vertical jumping (Gheller et al., 2015).

However, a contentious issue when attempting to understand the coordinated motion of body components is the methodology employed to quantify coordination and its inherent variability (Hamill et al., 2000). Continuous methods permit the evaluation of movement coordination throughout a cycle of movement, providing spatial and/or temporal evaluation of coordination and greater insight compared with discrete methods (e.g. discrete relative phase) (Wheat & Glazier, 2005). Two
primary continuous methods that measure coordination are continuous relative phase and vector coding (Hamill et al., 2012; Wheat & Glazier, 2005; van Emmerik, Miller, & Hamill, 2014). Before reviewing each method, it should be noted that both have been widely adopted in empirical studies and the chosen method should emerge with the particular research question (Hamill et al., 2000).

2.4.1.1 Continuous Relative Phase (CRP)

The method of CRP provides a measure of the phase relation between two oscillating components, calculated as the difference between the respective phase angles of the two oscillators (Hamill et al., 2000; Wheat & Glazier, 2005). The calculation of CRP therefore begins with obtaining a phase-plane portrait for each oscillator, by plotting angular velocity against angular position. A four-quadrant arctangent angle is then calculated from the phase-plane at each instance of the normalised time cycle, named the phase angle (Hamill et al., 2000). By subtracting the distal phase angle from the proximal, the CRP angle is obtained, which quantifies the coordinated nature of two body components (Wheat & Glazier, 2005). CRP angles are presented between 0° (in-phase) and 180° (anti-phase), with any angle between these extremes indicating a relative amount of in- or anti-phase coordination (Hamill et al., 2012). CRP variability can be subsequently calculated as the standard deviation, on a point-by-point basis, of multiple CRP plots (Hamill et al., 2000).

CRP is often considered a higher order measure of coordination between two segments or joints, by incorporating both position and velocity information to provide spatio-temporal analysis of movement coordination (Wheat & Glazier, 2005; van Emmerik et al., 2014). However, limitations to CRP have been presented, with underlying assumptions of sinusoidal motion of the two oscillators (van Emmerik et al., 2014) questioning its use for the assessment of lower limb coordination in many sports movements (Wheat & Glazier, 2005). Furthermore, normalisation of angular position and velocity data in the phase-plane are required (Peters, Haddad, Heiderscheit, van Emmerik, & Hamill, 2003), with different methods used to normalise angular velocity (unit circle or maximum velocity) shown to effect the value of CRP obtained (Hamill et al., 2000). Finally, the output measure of CRP can be difficult for practitioners to relate conceptually, with respect to interpreting the type and nature of the relationship between joints or segments (Kurz & Stergiou, 2002; Wheat & Glazier, 2005; Tepavac & Field-Fote, 2001). Therefore, it has been
suggested that vector coding methods may provide a better means of assessing coordination when the focus is to enhance understanding of the spatial relationships between body components (van Emmerik et al., 2014).

2.4.1.2 Vector Coding

The origins of vector coding reside in the quantification of relative motion plots, also known as angle-angle diagrams (Sparrow et al., 1987). Relative motion plots are useful in qualitatively describing coordination patterns between two segments or joints, first introduced by Grieve (1968) as a simple method to interpret movement patterns in the lower limb during gait. Early methods to quantify relative motion plots included chain coding techniques and cross correlation to compare the similarity between two encoded curves (Freeman, 1961). However, not recognising that data are not equally spaced in human movement, alongside converting data from ratio to nominal scales, were viewed as major limitations to the chain coding technique (Sparrow et al., 1987; Tepavac & Field-Fote, 2001).

Sparrow et al. (1987) provided the first form of modern vector coding methods, by calculating the angle between successive points on the relative motion plot relative to the right horizontal. Sparrow (1987) introduced modified cross correlation functions to compare coordination patterns, accounting for the difference in lengths between each data points that was absent in Freeman's method (Freeman, 1961). Tepavac & Field-Fote (2001) expanded the method by Sparrow et al. (1987) by introducing circular statistics to the calculated angle between successive points, providing a method that allows the variability of multiple cycles of the same movement to be compared simultaneously (Wheat & Glazier, 2005).

Modern vector coding methods (Chang et al., 2008; Needham et al., 2014), introduced by Hamill et al. (2000), adopted the technique used by Sparrow et al. (1987) to calculate the orientation of successive points on the relative motion plot, terming the output variable as a 'coupling angle' (Fig. 2.4). The coupling angle has been related to the field of biomechanics as a method to compare oscillating components that can be easily interpreted back to the relative motions on the angle-angle plot (Wheat & Glazier, 2005). The resulting coupling angle ranges between 0° and 360°, from which different patterns of coordination can be interpreted based on the relative motion of the proximal and distal components (Hamill et al., 2000; Heiderscheit et al., 2002; Chang et al., 2008). Whilst Hamill et al. (2000) initially
described coordination patterns at explicit 45° increments, Chang et al. (2008) later developed distinct classifications, or ‘bins’, to describe rear foot-forefoot coordination patterns (Fig. 2.4). The binning method developed by Chang et al. (2008) has provided a means to quantify dominant coordination patterns during a particular movement, by undertaking frequency analysis of the different coordination patterns (e.g. Chang et al., 2008; Freedman-Silvernail, van Emmerik, Boyer, Busa, & Hamill, 2018; Needham et al., 2014).

Figure 2.4. Schematic of the coupling angle (CA) calculation based on adjacent points of an angle-angle plot. The resulting CA can be classified into particular ‘bins’ representing distinct coordination patterns: proximal phase = proximal movement whilst distal remains still; distal phase = distal movement whilst proximal remains still; in-phase = both oscillators moving in the same direction; anti-phase = oscillators moving in opposite directions. Adapted from Chang et al. (2008).
Due to the directional nature of the coupling angle, authors have adopted circular statistics (Batschelet, 1981) to calculate average coupling angle and its variability across a number of trials (Chang et al., 2008; Hamill et al., 2000; Heiderscheit et al., 2002; Needham et al., 2014). By calculating the variability in coupling angle data, a profile of coordination variability can be presented across the normalised time cycle (Heiderscheit et al., 2002) or further quantified to discrete values of variability (Wilson et al., 2008).

2.4.1.4 Section Summary
In summary, both CRP and vector coding provide a means of understanding the interacting motion of two body segments, measuring movement coordination and its associated variability (Hamill et al., 2000). Whilst it should be acknowledged that the method used may affect the variability results (Wheat, Mullineaux, Bartlett, & Milner, 2002; Miller, Chang, Baird, van Emmerik, & Hamill, 2010), with CRP being suggested as the more sensitive measure (Wheat et al., 2002), the final decision should reflect the research question (Hamill et al., 2012).

If the research question is to investigate the spatial coordination and variability of two joints or segments, vector coding is potentially the better choice (van Emmerik, 2014). To the authors’ knowledge, vector coding has not been applied in the strength and conditioning setting in order to understand the movement specificity of a training exercise in relation to a competitive motor task. The extra detail provided by coordination analysis when understanding human movement, offers a fruitful avenue for the analysis of movement specificity (Irwin & Kerwin, 2007a; Wilson et al., 2009).

2.4.2 The Functional Role of Variability for Sports Performance
As movement arises through self-organisation under imposed constraints (Newell, 1986), variability in movement coordination is inherent between and within all biological systems (Bates, 1996; Newell & Corcos, 1993; Newell et al., 2006; Preatoni et al., 2013; van Emmerik & van Wegen, 2000). This perspective on movement variability opposes traditional cognitivist theories of motor control that regard variability as an unwanted source of error and is detrimental to performance (Schmidt, 1975). Fundamentally, variability has two different forms: noise due to measurement error and variation due to inherent dynamics of the system (van Emmerik & van Wegen, 2002). Variability from a dynamical systems perspective is
not inherently good or bad, but indicates the range of coordinative patterns that can be used to complete the motor task (van Emmerik et al., 2014). Therefore, dynamical systems theory promotes a functional role of coordination variability, as a necessary component to ensure consistent performance outcomes in response to changing constraints on action (Bartlett et al., 2007; Davids et al., 2003; Glazier, 2015; Hamill et al., 2012).

This adaptability in our biological system allows for learning a new movement or adjusting a known movement by searching for the most appropriate coordination solution to achieve the task (Newell et al., 2006; Preatoni et al., 2013). In addition, coordination variability may be a characteristic of healthy function, with empirical research establishing a link between reduced coordination and pathological gait (van Emmerik, Wagenaar, Winogrodzka, & Wolters, 1999), the loss of postural stability with age (van Emmerik & van Wegen, 2002), patellofemoral pain in runners (Hamill et al., 1999; Heiderscheit, 2002), and increased ACL injury risk (Pollard, Heiderscheit, van Emmerik, & Hamill, 2005). Understanding the functional properties of variability can have vast implication for the analysis of sporting technique, monitoring skill development and strength and conditioning (Bartlett et al., 2007; Davids et al., 2003; Glazier, 2015; Preatoni et al., 2013).

Early insight to the function role of coordination variability for sports performance was established in the pioneering study by Arutyunyan, Gurfinkel & Mirskii (1968) studying novice and expert pistol shooters. Findings demonstrated that expert pistol shooters exhibited lower end-point variability (the ability to hold the barrel of the pistol steady) but increased coordination variability between the shoulder, elbow and wrist, explaining that the variability in joint motions can help maintain consistent task outcome. The link between increased coordination variability facilitating consistency in task outcome was also provided by Wilson et al. (2016), who observed decreases in coordination variability but increased variability in leg press power output in older adults compared with healthy, younger adults. Coordination variability may therefore be reflective of utilising the redundancy (Bernstein, 1967) or abundance (Latash, Scholz, & Schöner, 2002) in our biomechanical degrees of freedom to afford flexibility in executing motor tasks and achieving consistent task outcomes (Bernstein, 1967; Davids et al., 2003; Hamill et al., 1999; Holt, Jeng, Radcliffe, & Hamill, 1995; Kelso, 1995; Latash et al., 2002; van Emmerik et al., 2005).
Within the context of sports performance, elite athletes have shown variability in movement patterns are shown even after years of practice (Bartlett et al., 2007; Bradshaw, Maulder, & Keogh, 2007; Davids et al., 2003), indicating that there is an opportunity for inherent biological variability to be promoted in a functional manner within elite sport performance. Previous evidence within basketball shooting has demonstrated that expert performers can exploit increased variability of the distal joints to maintain consistent ball release parameters linked to task success (Robins, Wheat, Irwin, & Bartlett, 2006). Furthermore, during the hop-step transition in the triple jump, a non-linear, U-shaped relationship between task expertise and intra-limb coordination variability has been established, suggesting that increased variability is characteristic of least and most skilled athletes (Wilson et al., 2008). The U-shaped relationship between expertise and coordination variability shown by Wilson et al. (2008) provided support for Newell’s (Newell, 1985) stages of learning, showing how variability in coordination patterns might be exploited differently as task expertise progresses, initially to explore patterns of coordination and later to provide flexibility to adapt to environmental perturbations (Wilson et al., 2008). Whilst the small sample size might be a limitation of Wilson et al. (2008), subsequent research in race walking has supported their results by showing an increase in variability in more skilled vs. less skilled walkers (Preatoni, Ferrario, Donà, Hamill, & Rodano, 2010).

The major conclusion of the aforementioned research is that successful task outcome may require the exploitation of inherent variability in the motor system to ensure a flexible system that can adapt to perturbations (Hamill et al., 1999; Wilson et al., 2008). However, a functional bandwidth of variability may exist (Bartlett et al., 2007; Glazier & Davids, 2009; Robins et al., 2006), with its magnitude and functionality likely dependent on the constraints associated with the task (Vaillancourt & Newell, 2002). To date, the author is not aware of any empirical research investigating intra-limb joint coordination variability in the block start action, or assessing the relationship between coordination variability and sprinting performance level. Furthermore, dynamical systems theory provides an insightful avenue to understand the principles of training within exercise selection (Irwin & Kerwin, 2007a; Wilson et al., 2009), from the constraints based approach to motor control (Newell, 1986).
2.4.3 The Application of Dynamical Systems Theory to Strength Training

The fundamental goal of strength training is to improve the ability of an individual to generate task specific force that can enhance sports performance (Newton & Kraemer, 1994; Siff & Verkoshansky, 1999). This goal is inherently linked within dynamical systems theory and Newell’s model of constraints (Newell, 1986) in that changes in neuromuscular strength can be reflected as changes to the unique organismic constraints of the individual athlete. As organismic constraints influence emergent coordination patterns through self-organisation (Newell, 1986), the increased ability of the neuromuscular system to produce force that can occur through strength training (Suchomel et al., 2016) may subsequently result in alterations in coordination patterns to achieve the competitive motor task.

Alterations to movement pattern is often viewed by coaches as the drawback of non-specific strength training and it is perceived that time is required for increased neuromuscular potential to be utilised effectively within the sporting movement (Burnie et al., 2017). Taking a dynamical systems approach to movement specificity, the transfer of altered organismic constraints to improved sports performance may be improved by ensuring similarity in movement coordination (Irwin & Kerwin, 2007a; Wilson et al., 2009). Therefore, if organismic constraints can be favourably altered through strength training (overload), in a way that promotes coordinative structures associated with task performance (specificity), this could provide the most effective means of achieving positive training transfer.

Understanding movement specificity from a coordinative perspective may provide greater insight towards most appropriate exercise selection for enhancing the performance of a competitive motor task (Irwin & Kerwin, 2007a; Wilson et al., 2009). For example, the rank order of specificity scores for gymnastics long swing progressions exhibited disagreement when considering single joint kinematics (Irwin & Kerwin, 2005) and inter-segmental coordination (Irwin & Kerwin, 2007a). The results of Irwin & Kerwin (2005; 2007a) suggested that only considering isolated joint mechanics may limit the evaluation of movement specificity between a training exercise and competitive motor task.

Other research has used coordination measures to compare movement specificity of triple jump drills (Wilson et al., 2009), although a lack of research has explicitly compared intra-limb coordination between a competitive motor task and strength
exercises that aim to elicit neuromuscular adaptation through the principle of overload. In most cases, intra-limb coordination analyses of strength training exercises has occurred in the absence of a competitive motor task, examining the squat (Scholz, Millford, & McMillan, 1995) and a range of lower body resistance exercises (Romanazzi et al., 2015) in isolation.

In the study by Romanazzi et al. (2015), results showed no significant differences in lower limb joint angular displacements between the deadlift, forward lunge and step up exercise. However, CRP analysis revealed inter-exercise differences in intra-limb coordination (Romanazzi et al., 2015), highlighting that intra-limb coordination permits a more detailed understanding of movement (van Emmerik et al., 2014; Hamill et al., 1999). Furthermore, Romanazzi et al. (2015) demonstrated that differences in coordination patterns can arise between tasks with the same functional goal: to overload the lower limb musculature during leg extension.

A final consideration when applying dynamical systems theory to the principles of training and exercise selection within strength and conditioning is the influence of the individual athlete (Ives & Shelly, 2003). Alongside inherent organismic differences between individuals (Newell, 1986), the redundancy in available solutions within our biological system provide individuals the opportunity to achieve motor tasks utilising different strategies (Bernstein, 1967; Bartlett et al., 2007; James & Bates, 1997; Bradshaw et al., 2007). From a biomechanical perspective, individual techniques may influence the principles of overload and specificity and affect subsequent neuromuscular adaptation, affording explanation to observations of individual responses throughout the scientific literature (Astorino & Schubert, 2014; Bouchard & Rakinen, 2001; Hubal et al., 2005; Karavita et al., 2011; Newton et al., 2002). With respect to the examination of training principles within exercise selection, empirical evidence therefore suggests that the individual athlete should be recognised.

In summary, the principles of training (Matveyev, 1981; Siff & Verkoshansky, 1999) can be seamlessly embedded within the framework of constraints (Newell, 1986) inherent to dynamical systems theory. The principle of overload reflects changing the unique organismic constraints of the individual athlete, with the principles of specificity governing how these altered organismic constraints can be managed to promote the self-organisation of coordination structures that are functionally linked.
to competition task execution. To advance understanding of the principles of training within exercise selection, holistic evaluations of a training exercise should occur that consider the nature of overload from a musculoskeletal perspective, and the specificity of movement through analysis of intra-limb coordination and its inherent variability.

2.5. Methodological Considerations
The study of human movement requires the collection and processing of a range of biomechanical data, most often including motion and ground reaction forces in order to quantify the kinematics and kinetics of motor tasks. The best methods for collecting, processing and analysing data often lie with the demands of the specific investigation. The purpose of the following section is to review key aspects of biomechanics research methods and their application to the analysis of the block start in athletic sprinting and strength training exercises.

2.5.1 Data Collection
2.5.1.1 Motion Analysis
Within biomechanics, motion data is often acquired using either video cameras or automated motion capture systems (Payton, 2008). Both systems provide means of obtaining coordinate reconstruction of body segments, which are subsequently processed to obtain kinematic variables that describe movement. Whilst automated systems are more commonly adopted in modern biomechanics research (Robertson & Caldwell, 2014), video-based analysis has a number of practical advantages, including low cost, environmental flexibility and minimal interference to the performer (Payton, 2008). However, advancements in technology has made the utilisation of automated three-dimensional (3D) motion capture systems common practice within biomechanics research environments. Although the external validity of automated systems can be questioned as they are usually installed in laboratories, they can be used outside the laboratory to permit data collection within the performance environment. The main advantage of automated systems include the accurate and precise collection of large amounts of data with high sampling frequencies and minimal processing time (Robertson & Caldwell, 2014; Milner, 2008).
Automated motion capture systems can be either active or passive, requiring cameras to locate the position of makers attached to the participant in order to determine the position and orientation of body segments. Whilst active markers emit their own light source, passive systems rely on the reflection of infra-red light by spherical markers that are detected by multiple cameras (Milner, 2008). Passive systems often use multiple cameras organised around the performance area, creating capture volume by which the exact placement and orientation of each camera is not as critical as with video analysis (Robertson & Caldwell, 2014). Passive motion capture systems require calibration to enable image coordinates to be converted to real-world 3D coordinates for each marker, involving both static (defining the location of the origin and orientation of the capture volume) and dynamic (registering each camera to the whole capture volume) calibration (Milner, 2008). A good calibration is fundamental to the accurate recording of markers in 3D space, with each camera providing a residual error, which is the precision that the marker positions can be located, often provided in millimetres (Milner, 2008).

A recognised limitation with any automated system is that markers must be used which can be disruptive to performance, and induce high-frequency noise due to the movement of the underlying tissue. In contrast, video analysis increases sources of noise in the manual digitising process. Therefore, regardless of the motion capture methods used, coordinate data must be filtered prior to processing of kinematic data.

2.5.1.2 Ground Reaction Forces

Ground reaction forces (GRF) represent the equal and opposite reaction force of an action force applied to the ground by a body, based on Newton’s third law of motion (Knudson, 2007). Within biomechanics, GRF are measured through force platforms, which comprise a number of force transducers within a rigid plate, which are often imbedded into the ground (Lees & Lake, 2008). Data from force platforms has been widely used to understand sports technique (Willwacher et al., 2016), also facilitating the calculation of joint kinetics through inverse dynamics (Bezodis et al., 2014).

Two types of force platform are commercially available, strain gauge and piezoelectric. Piezoelectric force platforms have tri-axial sensors to measure 3D forces and have greater frequency range and sensitivity compared with strain gauge systems (Caldwell, Robertson, & Whittlesey, 2014), with Kistler force platforms
measuring force ranges from 10 to 10,000 N with an accuracy of 1% (Kerwin, 1997). Force is a vector property defined by its magnitude, direction and point of application (Caldwell et al., 2014). The point of force application from piezoelectric force platforms is computed from the relative vertical forces from each of the four load cells that are located in each corner of the plate, equidistantly from the centre. This point of force application is also known as the centre of pressure (COP), which is required during inverse dynamics analysis in the calculation of joint moments. The accuracy of COP coordinates decreases with proximity of the load cells, especially when force is applied outside the load cell boundaries (Bobbert & Schamhardt, 1990). Therefore, best practice suggests that contact should be made towards the centre of the platform, although this can lead to targeting during locomotive tasks (Exell, Gittoes, Irwin, & Kerwin, 2012).

2.5.2 Data Processing
2.5.2.1 Estimating Segment Pose Using Passive Markers
When using automated 3D motion capture systems, the position of each body segment is estimated based on the markers attached to the body. To define a segment’s position and orientation in 3D space, three non-collinear markers are required, which are placed at the proximal and distal endpoints of the segment, to represent joint centres (Milner, 2008). A static calibration will define the segments of the body in the 3D capture volume, and the user can choose to use these markers to track segmental motion or use rigid clusters placed on the segments. Modern gait analysis laboratories often use clusters of four markers attached to a rigid material that are then placed onto the segment (Milner, 2008).

During static calibration, the orientation of the cluster relative to the calibration markers is defined, so that the cluster can be used to track the pose of the segment during the motion trial. This offers benefits over simply using calibration markers, as it affords greater flexibility in camera placement and reduces the high frequency noise of markers placed directly onto the skin (Milner, 2008). The positioning of clusters is often recommended at the middle of the segment, although empirical research has suggested a more distal placement for measuring tibia rotation (Manal, McClay, Stanhope, Richards, & Galinat, 2000).
2.5.2.2 Signal Filtering

Both kinematic and kinetic data signals are composed of the true signal and noise (Challis, 2008), with noise arising from multiple sources including skin movement, electrical interference, or other artefacts that have different characteristics from the true signal (Derrick, 2014). For many biomechanical analyses, it is necessary to reduce the random noise that contaminates the true signal (Challis, 2008). As most noise in biomechanical data is of higher frequency than the observed movement, low pass digital filters are commonly used to remove high frequency noise, a process also known as smoothing (Derrick, 2014). Digital filters are a type of moving average, weighted by coefficients that afford the user control over the cut-off frequency, which determines the frequency at which signals pass through the filter unaffected (Bartlett, 2007). The Butterworth digital filter is most commonly used in biomechanics research (Mullineaux, 2017), with data usually passed bi-directionally to remove any time shift (Derrick, 2014). Because digital filters generally distort time series data at end-points, it is recommended that data be collected in excess of the movement time so that the ends are padded (Derrick, 2014).

A main consideration for biomechanists using digital filters is the choice of cut-off frequency, with recommendations between 4 and 12 Hz being advocated for most sporting movements (Bartlett, 2007; Milner, 2008). Various methods have been established to determine the optimal cut-off frequency, with residual analysis (Winter, 2009) and autocorrelation (Challis, 1999) being the dominant methods in biomechanics literature. During residual analysis, the raw data are filtered at different cut-off frequencies and the residuals between the filtered and raw data are determined. The optimal cut-off frequency is then selected at which the residual-frequency plot approaches an asymptotic value (Winter, 2009).

Residual analysis, whilst being widely accepted and used (Bezodis et al., 2008; Hunter et al., 2004b), can be labour intensive and includes subjectivity in the visual assessment of the residual-frequency graph (Challis, 1999). Automated methods such as the autocorrelation method proposed by Challis (1999), offer a more objective method to select the optimal cut-off frequency, by using the autocorrelation function to determine the frequency at which the difference between the filtered and unfiltered data best approximates white noise. While it is still unclear which method of selecting the optimal cut-off frequency is superior, the method by Challis (1999) is the more objective, although this may not necessarily be of benefit due to
anomalies introduced during the filtering process. Residual analysis allows the researcher to interact with the data to assist the best decisions based on the dataset, however methods to increase objectivity have been proposed, such as curve rotation to identify the breakpoint in the residual-frequency plot (Mullineaux, 2017).

2.5.3 Data Analysis

2.5.3.1 Inverse Dynamics Analysis (IDA)

The computation of joint kinetic data using IDA is important to biomechanics research to investigate the musculoskeletal demand experienced when executing a task. IDA has been utilised in many studies to analyse phases of sprinting (Belli et al., 2002; Bezodis et al., 2014; Mero et al., 2006) and strength training exercises (Swinton et al., 2011; Jandacka et al., 2014), providing an unobtrusive means to approximate net joint moments, powers and work using known segment inertial properties, kinematics and GRF data (Whittlesey & Robertson, 2014).

The uncertainties associated with IDA are well documented, with sources of error arising from the input data (GRF, centre of pressure, joint centre locations, segment inertial properties, segment accelerations) and data treatment techniques (e.g. filtering) (Belli, Kyröläinen, & Komi, 2002; Bezodis, Salo, & Trewartha, 2013; Challis & Kerwin, 1996). Of these inputs, errors in kinematic data have been suggested to have larger influence on the uncertainties associated with IDA calculations, reflecting noise in the derived segment accelerations and location of joint centres (Challis & Kerwin, 1996). When performing IDA, noise reduction (filtering) procedures and consistency in marker placement are therefore significant factors relating to the accuracy of the outcome.

2.5.3.2 Segment Properties

Estimations of body segment inertia parameters have been performed using numerous methods, allowing the estimation of segment masses, centre of mass location and moments of inertia that are required for IDA. Methods have included ratio and regression equations from cadaver study (Dempster, 1955), geometric modelling (Hanavan, 1964; Yeadon, 1990) and medical imaging techniques (Zatsiorsky & Seluyanov, 1983; de Leva, 1996). Ultimately, the choice of method will affect the IDA results, although uncertainties associated with the inertial model used have been shown to be smaller than the uncertainties with kinematic data (Challis & Kerwin, 1996). Whist obtaining segment mass from cadaver study
(Dempster, 1955) has been criticised for not reflecting healthy athletic populations (Yeadon, 1990), its use in combination with geometric modelling of inertial characteristics (Hanavan, 1964) is promoted in industry leading software to analyse biomechanical data (C-Motion Inc, Germantown, USA). Ultimately, whilst small differences in the outcome of IDA can result from different inertial models, for the current research question the most important factor is that the same model is used throughout the study.

2.5.3.3 Statistical Analysis

One of the main uses of statistics evident in the literature is that of statistical significance testing of the null hypothesis (NHST) (Mullineaux, 2008). Inferential NHST involves calculating the probability (P-value) that an observed effect did not occur by chance, with \( P < 0.05 \) often used to suggest that the differences between datasets are ‘significant’ (Mullineaux, Bartlett, & Bennet, 2001). More recently, inferential NHST has received criticism, by not recognising the magnitude of an effect and philosophically viewing the world as black or white (yes or no) (Batterham & Hopkins, 2006; Bernards, Sato, Haff & Bazyler, 2017; Hopkins, Marshall, Batterham, & Hanin, 2009).

Effect sizes, especially Cohen’s \( d \) (Cohen, 1988) provide a measure of the magnitude of an effect, by calculating a standardised score that reflects by how many standard deviations the group means differ (Mullineaux et al., 2001). The use of effect sizes is now widely advocated in sports science literature (Bernards et al., 2017), interpreting the magnitude of \( d \) to the size of the difference between group means. Initially Cohen (1988) provided guidelines to interpret the effect size, with values of 0.1, 0.3 and 0.5 being the threshold for small, moderate and large effects. Later, Hopkins (2002) extended these guidelines for sport and exercise, identifying values of 0.2, 0.6, 1.2, 2.0 and 4.0 as thresholds for small, moderate, large, very large and extremely large effects. The use of effect sizes provide an alternative or supplement to NHST, providing greater insight to the magnitude and therefore practical importance of an effect (Hopkins, 2009).

The confidence interval (CI), defined as the likely range of the true value within a given probability, can offer supplementary use with effect sizes to help identify the precision of an effect and the likely range of the true effect (Batterham & Hopkins, 2006). This has provided the foundation for magnitude-based inferences (MBI),
developed philosophically to recognise the importance of estimating the true value of an effect, compared with the bases of NHST that attempts to disprove that there is no effect (Batterham & Hopkins, 2006). MBI provides a method to make inferences about the mechanistic (positive, trivial, negative) meaningfulness of an effect based on the probability that the true value of the effect is larger than a predetermined smallest meaningful difference (Batterham & Hopkins, 2006).

The smallest meaningful difference can be based on subjective assessment of what is considered a meaningful effect, perceived as a benefit over NHST as it necessitates that the investigator adopts a conscious process when analysing data (Buchheit, 2016). Often, a smallest meaningful difference of 0.2 is chosen (Winter, Abt, & Nevill, 2014). The percentage likelihood that the observed effect is larger than the smallest meaningful difference can then be assessed and qualitative terms are assigned to the inference (e.g. likely, very likely, almost certainly meaningful) (Batterham & Hopkins, 2006). The MBI approach to differences between means can also be applied to correlational analysis, calculating confidence intervals around the magnitude of ‘r’ to interpret the likelihood of the true correlation being greater than a smallest meaningful value of $r = 0.1$ (Hopkins, 2009).

MBI has not been universally accepted with statisticians, who often criticise its increased chance to inflate type 1 error rates (false discovery of no effect), inclusion of researcher bias during interpretation, and not representing a true Bayesian approach (Bernards et al., 2014; Welsh & Knight, 2015). However, despite its criticism, MBI offers a practical solution for quantifying the meaningfulness of an effect, with elements of Bayesian thinking that is particularly fruitful for the study of elite athletes with low sample size (Hopkins & Batterham, 2016; Mengersen, Drovandi, Robert, Pyne, & Gore, 2016; Wilkinson, 2014).

2.5.4 Research Design
2.5.4.1 Single Subject Research Design
In sports biomechanics, a dynamical systems approach to movement coordination and coordination variability helps to explain how individual athletes can achieve the same motor tasks through different biomechanical strategies (Dufek & Bates, 1990), or the same athlete demonstrates variability in technique (Bradshaw et al., 2007). The uniqueness in movement coordination even though our basic physiology is similar, has advocated the use of single subject (within athlete) research designs for
supplementing group level analyses (Bates, 1996; James & Bates, 1997). Grouping participants is common practice in biomechanics research, mainly to increase statistical power, although this can lead to inferences being made on the mythical average performer that is not fully representative of any of the individuals (Bates, 1996).

The benefit of single-subject designs has been shown empirically during landing tasks in which individual landing strategies were identified that were masked by group analyses (Dufek & Bates, 1990; Dufek, Bates, Stergiou, & James, 1995). Although single-subject methodologies have been recognised to lack generalisability (Bates, 1996), a combination of both group and individual analyses may provide the most holistic way of understanding of the biomechanics of sports technique and the characteristics related to higher levels of performance.

2.6 Chapter Summary
The literature reviewed in this chapter has offered insight into theories and practice within strength training, dynamical systems theory and its application to strength training, and the biomechanics of the block start in athletic sprinting that was established as the competitive motor task in the current research. A dearth of research has combined common joint level biomechanical analyses of kinematics and kinetics with measures of intra-limb coordination, to evaluate the principles of overload and specificity within exercise selection.

To ensure any investigation into the principles of overload and specificity is relevant to the performance determinants of the competitive motor task, further insight into the block start in athletic sprinting is also warranted, addressing gaps in the literature with respect to lower-limb musculoskeletal demand and joint coordination. The following Chapters have emerged to address specific research questions that will help achieve the overall thesis aim and advance conceptual understanding of the principles of training within exercise selection.
CHAPTER 3. A BIOMECHANICAL ANALYSIS OF BLOCK START TECHNIQUE

3.1 Introduction

In Chapter 2, it was emphasised that biomechanical understanding is essential to ensure training is most relevant to the sport (Moir et al., 2018) and to investigate the principles of overload and specificity with respect to a competitive motor task (Siff & Verkoshansky, 1999; Stone et al., 2002). Given the importance of the block start to overall 100 m sprint performance (Willwacher et al., 2016), previous empirical research has attempted to understand the biomechanics of this sports skill. Analysis themes have included external kinetics (Baumann, 1976; Mero et al., 1983; Otsuka et al., 2014; Willwacher, Herrmann et al., 2013, Willwacher et al., 2016), joint kinematics (Bezodis et al., 2015), segment kinetic energy (Slawinski, Bonnefoy, Ontanon et al., 2010), and joint kinetics (Mero et al., 2006; Otsuka et al., 2015). However, rarely have these different themes been holistically understood in the same population of sprinters, and joint kinetics have yet to be quantified in detail. Additionally, it is paramount for this research that a biomechanical analysis of block start technique is undertaken in the same population of sprinters that will be used to evaluate training exercises.

Aside from an in depth understanding of the biomechanics of the block start, biomechanists, coaches and strength and conditioning practitioners are often interested in identifying the variables that are associated with superior performance. Previous evidence based research has identified several key external kinetic variables separating different levels of sprint ability, including: greater front and rear block rate of resultant force development (Willwacher, Herrmann et al., 2013), more balanced front and rear peak resultant force (Willwacher, Herrmann et al., 2013), greater rear block peak force (Fortier et al., 2005) and greater total (front + rear) average horizontal force (Otsuka et al., 2014). Interpreting the relative importance of external force applied to the front and rear block from the aforementioned studies can be difficult, which may be accounted for by the different athletes used, different statistical analyses, or that between-group analyses have not been based solely on block performance. However, it has recently been concluded in a large sample of 158 sprint athletes, that the magnitude of horizontal force applied to both blocks is essential to maximise block start performance (Willwacher et al., 2016).
Although external kinetic analyses provide valuable insight into starting block performance, analysis at the level of joints or segments can reveal techniques that are adopted by more successful performers. In the study by Mero et al. (2006) graphical representation of joint kinetic data revealed that large extensor moments and power generation were observed at both hip joints during the block start. The importance of the hip joint towards block start execution has been more recently supported, with observations of large kinetic energy of the thigh segments during the starting action (Slawinski, Bonnefoy, Ontanon et al., 2010) and significant relationships between hip angular velocity and block performance (Bezodis et al., 2015).

Understanding lower limb joint kinetics allows for an increased understanding of the causes of segment motion that are responsible for CM acceleration. However, to the authors’ knowledge the joint kinetic determinants of external force production, as well as overall block performance is not yet known. By understanding the relationships between internal kinetics, external kinetic, and starting block performance, more focused training strategies and analyses of training exercises can flourish.

Chapter 3 seeks to address the identified gaps in previous literature and provide a foundation of knowledge to use when moving towards the proceeding chapters in this thesis. The overall aim of the chapter was to investigate the biomechanical demand of executing the block start and the kinetic determinants of performance. For the purpose of analysis and discussion, the results and discussion sections are separated into two parts to address the two key themes of the chapter and answer the following research questions:

Theme 1: Biomechanics of the Block Start

Research Question 1 – What are the external kinetic and lower limb joint kinematic and kinetic characteristics of block start technique?

Research Question 2 – How are the biomechanics of the block start different between the front and rear block / leg?
**Theme 2: Biomechanical Determinants of Block Start Performance**

**Research Question 3** – *Which external kinetic variables are associated with higher levels of block performance?*

**Research Question 4** – *What are the relationships between lower limb joint kinetics, external kinetics and starting block performance?*

Answering these questions will contribute to achieving the aim of the chapter. The purpose of this chapter was to increase understanding of the biomechanics of the block start and the key characteristics of successful performance. Performing this study will provide a foundation of information so that subsequent analysis of training exercises can be performed with knowledge of the nature of musculoskeletal demand of the competitive motor task.

### 3.2 Methods

#### 3.2.1 Participants
Seventeen male sprinters (mean ± SD: age, 23 ± 4 years; height, 1.79 ± 0.05 m; mass, 76.03 ± 5.40 kg) with 100 m personal best times ranging from 10.10-11.20 s (10.69 ± 0.33 s) gave written informed consent to participate in the study following institutional ethical approval. All athletes were free from injury at the time of data collection. Individual athlete information including block performance (NAHP) is presented in Table 3.1.

#### 3.2.2 Data Collection
A cross sectional study design was implemented to understand block start biomechanics and the key determinants of performance. Data were collected at the National Indoor Athletics Centre in Cardiff during normal block acceleration training sessions. After a coach prescribed warm up each athlete performed five (A and C) to six maximal 10 m sprints from blocks and three dimensional external force and kinematic data were collected during the block phase.
### Table 3.1. Athlete characteristics

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<th>Height (m)</th>
<th>Mass (kg)</th>
<th>Leg Length (m)</th>
<th>100 m PB (s)</th>
<th>60 m PB (s)</th>
<th>NAHP Rank (NAHP)</th>
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<td>1.77</td>
<td>76.97</td>
<td>0.942</td>
<td>10.35</td>
<td>6.68</td>
<td>0.497</td>
<td>9</td>
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<td>J</td>
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<td>1.75</td>
<td>71.77</td>
<td>0.883</td>
<td>10.96</td>
<td>6.97</td>
<td>0.496</td>
<td>10</td>
</tr>
<tr>
<td>K</td>
<td>19</td>
<td>1.83</td>
<td>70.98</td>
<td>0.901</td>
<td>11.18</td>
<td>7.09</td>
<td>0.493</td>
<td>11</td>
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<td>L</td>
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<td>1.72</td>
<td>74.17</td>
<td>0.834</td>
<td>10.95</td>
<td>6.99</td>
<td>0.484</td>
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<td>M</td>
<td>18</td>
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<td>11.00</td>
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<td>N</td>
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<td>1.83</td>
<td>77.63</td>
<td>0.908</td>
<td>10.68</td>
<td>6.93</td>
<td>0.472</td>
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<td>O</td>
<td>24</td>
<td>1.79</td>
<td>78.50</td>
<td>0.886</td>
<td>10.69</td>
<td>6.89</td>
<td>0.469</td>
<td>15</td>
</tr>
<tr>
<td>P</td>
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<td>1.75</td>
<td>80.36</td>
<td>0.863</td>
<td>10.73</td>
<td>6.88</td>
<td>0.467</td>
<td>16</td>
</tr>
<tr>
<td>Q</td>
<td>27</td>
<td>1.89</td>
<td>92.15</td>
<td>0.905</td>
<td>10.64</td>
<td>6.81</td>
<td>0.452</td>
<td>17</td>
</tr>
<tr>
<td>Mean</td>
<td>23</td>
<td>1.79</td>
<td>76.03</td>
<td>0.886</td>
<td>10.69</td>
<td>6.88</td>
<td>0.514</td>
<td></td>
</tr>
<tr>
<td>SD</td>
<td>4</td>
<td>0.05</td>
<td>5.40</td>
<td>0.034</td>
<td>0.33</td>
<td>0.18</td>
<td>0.043</td>
<td></td>
</tr>
</tbody>
</table>

To measure external force data, custom-made force instrumented starting blocks were utilised (Willwacher, Feldker, Zohren, Herrmann, & Brüggemann, 2013). The instrumented starting blocks consist of a very stiff steel base unit and separate block units for the front and rear blocks that can be attached to the base unit. Different block units were available for different block obliquities however all athletes self-selected a 50° orientation. Mounted on top of each block unit is a small force platform consisting of four piezoelectric load cells (9601A31, Kistler Instrumente AG, Winterthur, Switzerland) finished with standard material for starting blocks (see Figure 3.1 for technical schematic). Force data were sampled at 10000 Hz (post-processed to 1000 Hz), externally amplified (8 channel amplifier, 9865, Kistler), AD converted (16 bit) and stored on a laptop using customised Labview software (Willwacher, Feldker, Zohren et al., 2013). A standard starting signal was provided by the software by two loudspeakers positioned directly behind the starting blocks.

Kinematic data were collected using a 15 camera (3x MXF20, 12x MX) three dimensional motion analysis system (Vicon, Oxford Metrics, UK, 250 Hz). Cameras were mounted on tripods to create a custom capture volume in which the block start
could be measured (Fig. 3.2). All cameras were calibrated to 3000 points, to residual errors of < 0.3 mm using a 240 mm calibration wand. The origin of the capture volume was set with a right-handed orthogonal global coordinate system of X (medio-lateral pointing to the right), Y (anterior-posterior, pointing forwards) and Z (superior, pointing upwards).

Figure 3.1. Technical schematic drawing of one block force measuring unit in the sagittal (left) and frontal (right) plane. Adapted from Willwacher, Feldker, Zohren et al. (2013).

Figure 3.2. Schematic of data collection setup.
To collect marker trajectory data for the lower limbs, retro-reflective markers (14 mm) were attached to the participant’s skin bilaterally on the: iliac crest, posterior superior iliac spine, anterior superior iliac spine, lateral and medial femoral epicondyles, lateral and medial malleoli, first and fifth metatarsal heads, calcaneus, and head of the second toe (Fig. 3.3). Technical clusters comprising of four markers were attached towards the distal end of the thigh and shank segments (Manal et al., 2000).

Figure 3.3. Marker locations used to define a model of the lower limb. Unilateral is shown. Medial femoral epicondyle and malleoli markers were removed for the motion trials.
3.2.3 Data Processing

3.2.3.1 External Kinetic Data

Force signals from the instrumented starting blocks were low-pass filtered (4th order Butterworth, 120 Hz cut-off) prior to analysis. Force data were used to define the instance of block start (earliest detection in which the first derivative of either the front or rear resultant force-time curve > 500 N.s\(^{-1}\) and resultant force continued to rise to its maximum value) and block end (front block resultant force < 50 N), which defined the total block phase. The total block phase was separated into front (equal to the total block phase) and rear (defined between block start and rear block resultant force < 50 N) sub-phases.

For all external kinetic calculations, force signals were rotated from local to global coordinate systems with the x-axis pointing to the right, y-axis pointing forwards (running direction) and z-axis pointing upwards. Peak and average horizontal (F\(_Y\)), vertical (F\(_Z\)) and resultant (F\(_R\)) force were calculated for the rear block and front block using the respective rear and front force-time signals and were normalised to bodyweight. Total horizontal power was calculated from the product of the total (front + rear) force- and velocity-time signals, with velocity obtained through numerical integration of the total F\(_Y\) signal using the trapezium rule, and subsequently divided by body mass.

To quantify block performance the horizontal power-time signal was averaged over the duration of the block phase (AHP) and then normalised to body mass and leg length (see section 3.2.3.3) to obtain NAHP which was the criterion performance measure in the current study. The rear and front components of total horizontal power were calculated by multiplying the rear and front horizontal force-time signals, respectively, with the total horizontal velocity-time signal. Peak and average horizontal power (P\(_Y\)) for the rear and front block were then obtained from the respective power-time signal and normalised in the same way as NAHP.

3.2.3.2 Joint Kinematic & Kinetic Data

Kinematic marker trajectories were labelled using Vicon Nexus (v1.8.5) and gap filled when necessary using both spline and pattern functions. After labelling of marker trajectories further data processing was performed using Visual 3D software (C-Motion Inc, Germantown, USA). A nine-segment model of the lower limb (pelvis and bilateral thigh, shank, foot and toe) was created with hip joint centres defined
using regression equations (Bell, Brand & Pedersen, 1989). Knee and ankle joint centres were defined as the midpoint between the medial and lateral femoral epicondyles, and malleoli, respectively. The MTP joint centre was defined as the midpoint between the first and fifth metatarsal heads (Smith, Lake, & Lees, 2014). Segment mass (Dempster, 1955) and inertial characteristics (Hanavan, 1964) were consistent with the default values prescribed in Visual 3D.

A static calibration was used to define each segment’s local coordinate system (SCS). For each SCS the x-axis pointed to the right, y-axis pointed forwards and z-axis pointed upwards. Raw marker coordinates were low-pass filtered (4th order Butterworth) with a cut-off frequency of 12 Hz, determined as the average cut-off frequency from a residual analysis on all tracking markers (Winter, 2009). Joint angles were calculated as the transformation between two SCS described by an X, Y, Z Cardan sequence of rotations (Selbie, Hamill, & Kepple, 2014), with positive and negative angles representing flexion/dorsiflexion and extension/plantarflexion, respectively. Range of motion (ROM) was calculated as the difference in joint angle between discrete time points. Joint angular velocity (°/s) was calculated as the rate of change of the distal SCS relative to the proximal.

Newton-Euler inverse dynamics procedures (Selbie et al., 2014) were used to calculate resultant joint moments at the ankle, knee and hip joints and were resolved in the proximal SCS (see section 3.2.3.4 for definition of centre of pressure). Synchronisation of external force data with kinematic data in Visual 3D was achieved through a known voltage rise in both datasets triggered by the block software prior to the starting gun sound. Only x-axis (flexion-extension) data were reported to reflect the sagittal focus of sprinting. Joint power was calculated as the product of joint moment and angular velocity and the main phases of positive and negative power were identified (Fig. 3.10).

Peak positive joint power was quantified during joint extension. Joint work was then calculated for each phase by integrating power data (trapezium rule) which quantified energy absorption (negative power) and generation (positive power). Relative work ($W_{rel}$) was calculated as the percentage of each joint’s positive extensor work phase to the sum of all positive extensor work phases. Thus, $W_{rel}$ represented each joint’s contribution towards total leg extensor energy generation.
3.2.3.3 Data Normalisation

Calculated joint angular velocities (°/s), moments (Nm), powers (W), work (J), and AHP (W) were normalised according to the recommendations of Hof (1996), with the power adjustment outlined by Bezodis et al. (2010). Leg length for the normalisation procedures was taken as the sum of the thigh and shank segment lengths of the Visual 3D model. Angular velocities were normalised using gravity (g) and leg length (ll) \( \left( \frac{g}{\sqrt{ll}} \right) \), joint moments and work using bodyweight (BW) and leg length \( (BW \times ll) \), and power using mass, gravity and leg length \( (mass \times g^3 \times \sqrt{ll}) \).

3.2.3.4 Definition of Centre of Pressure

Initial testing revealed that errors were present in the estimation of COP towards the end of the block phase (Fig. 3.4), a likely result of the positioning of the true COP being outside of the lower piezoelectric load cells of the instrumented starting blocks (Bobbert & Schamhardt, 1990).

![Figure 3.4. Example centre of pressure (COP) data for the front block during the starting block phase. Medio-lateral (x) and anterior-posterior (Y) distances of COP from the origin of the instrumented starting block is presented in the local coordinate system of the starting blocks.](image)
Therefore, to permit the computation of joint moment data in Visual 3D, the centre of pressure (COP) was defined by creating a virtual landmark that projected the location of the MTP joint centre onto the surface of the starting blocks. The projected landmark was deemed more representative of the true COP location compared to the absolute location of the MTP joint (Mero et al., 2006) as it allowed the COP to travel distally along the block surface in the global Y-Z plane, as indicated in Figure 3.5.

To achieve the COP location the position and orientation of the block surface needed to be defined. The origin of each block was determined as the median position of a plane (between the toe and heel markers) projected to the base of the foot whilst the athlete’s foot was in contact with the blocks in the set position (i.e. the middle of the base of the foot). Another landmark was then created at a 50° angle to the origin at the location of the track surface. A medial landmark was then created using a medial offset or 0.05 m to the left of the origin marker. Using these three landmarks a hybrid block segment could be created for the left and right block. The location of the respective MTP joint centre could then be projected at a right angle.
onto this surface to define the COP for each block (Fig. 3.5). This virtual landmark allowed the COP to travel distally along the block surface when the foot moved, and was deemed more representative of the true COP location compared with the absolute location of the MTP joint centre (Mero et al., 2006).

3.2.4 Data Analysis

3.2.4.1 Theme 1 – Biomechanics of the Block Start
To achieve an understanding of the technical and musculoskeletal demand of executing the block start, the average of all successful trials was used for each athlete. External force, joint kinematic, and joint kinetic time-histories were normalised to 100% of the rear or front block phase using a cubic spline. Ensemble mean and standard deviation time histories were then produced to show the average and between-sprinter variation in kinematic and kinetic patterns. Group mean and between-athlete standard deviations were calculated for all discrete data using each athletes mean data from all trials.

To investigate the differences between the rear and front block, standardised effect sizes (d) were calculated and magnitude based inferences (MBI) were made using 90% confidence intervals and a threshold of 0.6 (moderate) for the smallest meaningful difference (Batterham & Hopkins, 2006). Effect size, confidence intervals and MBI data were calculated based on the formulas provided in the post-only crossover analysis spreadsheet by Hopkins (2006). The percentage likelihood of the true difference being at least moderately positive (>0.6) or negative (<-0.6) was used to make the following inferences: possibly (25-75%), likely (75-95%), very likely (95-99.5%), and almost certain (>99.5%). Any effect in which the percentage likelihood of a positive or negative effect was <25% was deemed not different. A meaningful difference was defined as any difference reaching at least a ‘likely’ difference. The direction of the effect indicated whether the front (positive) or rear (negative) block was greater in magnitude (more positive or less negative). All data were confirmed to be normally distributed (Shapiro-Wilk P > 0.05) prior to analysis.

3.2.4.2 Theme 2 – Biomechanical Determinants of Block Start Performance
To investigate the key external and internal kinetic determinants of performance, liner bivariate correlations and multiple regression techniques were employed using the best trial (NAHP) for each athlete. The decision to use each athlete’s best trial
reflected the primary interest of understanding the variables that discriminated between each sprinter's highest ability.

To assess the relationships between external kinetics, internal kinetics, and starting block performance (NAHP), Pearson correlation coefficients were calculated and magnitude-based inferences were made using 90% confidence intervals and a threshold of 0.1 for the smallest practically important correlation (Batterham & Hopkins, 2006). The percentage likelihood of the true correlation coefficient being substantially positive (>0.1) was used to make the following inferences: likely (75-95%), very likely (95-99.5%), and almost certain (>99.5%). Any correlation with a >5% chance of being both positive (>0.1) and negative (<-0.1) was deemed unclear. For this sample, r values of 0.33, 0.50 and 0.66 indicated the thresholds for likely, very likely and almost certain positive relationships.

To more completely understand the determinants of starting block performance, multiple regression analyses were performed at the external and internal kinetic level. Firstly, front and rear average \( F_Y \) were used as independent variables in a multiple regression with NAHP to understand the relationship between horizontal force production and block performance. Joint kinetic variables that possessed a likely \((r \geq 0.33)\) relationship with NAHP were then used as independent variables in a stepwise multiple regression with NAHP in order to investigate the main joint kinetic determinants of block performance. Consistency of the residuals for multiple regressions were evaluated using homoscedasticity and normality tests, and the Durban–Watson statistic assessed autocorrelation. All statistical analyses were performed using IBM SPSS Statistics (v. 22.0).

3.3 Theme 1 Results: Biomechanics of the Block Start

3.3.1 External Kinetics

Group mean (± SD) rear and front block times were 0.193 ± 0.010 s and 0.362 ± 0.015 s, respectively meaning the rear foot was in contact with the blocks for 53 ± 2% of total block time. Discrete external kinetic data for the front and rear block is presented in Table 3.2. Many possible to almost certain differences were observed, and revealed that peak \( F_Y \) was likely greater in the rear block \((d = -0.86)\), whereas peak \( F_Z \) \((d = 1.41, \text{very likely})\), average \( F_Z \) \((d = 1.82, \text{almost certain})\) and average \( F_R \)
(\(d = 1.31\), very likely) were greater for the front block (Table 3.2). Although peak \(F_Y\) was likely greater in the rear block, average \(F_Y\) (\(d = 0.66\)) was only possibly greater in the front block indicating disparity between peak and average values. The largest differences were found for peak (\(d = 5.85\), almost certain) and average \(P_Y\) (\(d = 6.59\), almost certain) which were greater for the front block (Table 3.2).

Table 3.2. External kinetic variables (mean ± SD) for the front and rear block. Standardised effect size (\(d\)) and 90% confidence intervals for between block comparisons are shown. Inferences are based on the likelihood of the true value of \(d\) being moderate (0.6 or -0.6).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Rear Block</th>
<th>Front Block</th>
<th>(d)</th>
<th>CI -</th>
<th>CI +</th>
<th>Inference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak (F_Y)</td>
<td>1.189 ± 0.126</td>
<td>1.080 ± 0.116</td>
<td>-0.86</td>
<td>-1.45</td>
<td>-0.27</td>
<td>Likely</td>
</tr>
<tr>
<td>Peak (F_Z)</td>
<td>1.015 ± 0.164</td>
<td>1.268 ± 0.178</td>
<td>1.41</td>
<td>0.82</td>
<td>1.99</td>
<td>Very Likely</td>
</tr>
<tr>
<td>Peak (F_R)</td>
<td>1.563 ± 0.195</td>
<td>1.665 ± 0.198</td>
<td>0.49</td>
<td>-0.11</td>
<td>1.09</td>
<td>Possibly</td>
</tr>
<tr>
<td>Average (F_Y)</td>
<td>0.568 ± 0.072</td>
<td>0.612 ± 0.053</td>
<td>0.66</td>
<td>-0.02</td>
<td>1.34</td>
<td>Possibly</td>
</tr>
<tr>
<td>Average (F_Z)</td>
<td>0.510 ± 0.088</td>
<td>0.662 ± 0.069</td>
<td>1.82</td>
<td>1.10</td>
<td>2.54</td>
<td>Almost Certain</td>
</tr>
<tr>
<td>Average (F_R)</td>
<td>0.778 ± 0.103</td>
<td>0.907 ± 0.083</td>
<td>1.31</td>
<td>0.60</td>
<td>2.02</td>
<td>Likely</td>
</tr>
<tr>
<td>Peak (P_Y)</td>
<td>0.383 ± 0.064</td>
<td>1.054 ± 0.141</td>
<td>5.85</td>
<td>5.27</td>
<td>6.43</td>
<td>Almost Certain</td>
</tr>
<tr>
<td>Average (P_Y)</td>
<td>0.165 ± 0.033</td>
<td>0.425 ± 0.041</td>
<td>6.59</td>
<td>6.00</td>
<td>7.18</td>
<td>Almost Certain</td>
</tr>
</tbody>
</table>

Time-series data of horizontal external force and power is presented in Figure 3.6. Both the total force and power curves demonstrated two distinct peaks, one when both feet were pushing against the blocks and the second only when the front leg remained in contact. Although both curves shared a double peak characteristic, the nature of this was asymmetrical and illustrated disparity between total force and power generation (Fig. 3.6). The overall peak in total horizontal force occurred with both legs in contact with the blocks, whilst overall peak power occurred when only the front leg was in contact (Fig. 3.6).
Figure 3.6. Group ensemble average (solid lines) and standard deviation (dotted lines) external force- (top) and power- (bottom) time histories. Data is shown for the rear block (grey dashed line), front block (grey solid line) and total block (black solid line) phase.

3.3.2 Joint Kinematics & Kinetics
Joint angle and range of motion (ROM) data are detailed in Table 3.3. Almost certain differences existed for all knee and hip joint data, indicating that the front knee and hip were placed in greater flexion in the set position and extended through a greater range of motion to a more extended position (Table 3.3). At the ankle joint, large inter-individual variability (rear block, -7.9 ± 6.9°; front block -2.5 ± 7.3°) meant that only a possible difference existed in ankle joint angle at the start of the block phase.
No difference was observed for peak dorsiflexion angle, leading to a likely greater dorsiflexion range of motion in the front block (-10.1 ± 4.3°) compared with the rear (-6.2 ± 3.4°). As peak dorsiflexion angle was not different, a greater peak plantarflexion angle in the front block (\(d = 2.80\), almost certain) lead to a greater plantarflexion range of motion in the front block (\(d = 1.91\), almost certain).

Table 3.3. Front and rear leg (mean ± SD) joint angle and range of motion (ROM) data. Standardised effect size (\(d\)) and 90% confidence intervals for between block comparisons are shown. Inferences are based on the likelihood of the true value of \(d\) being moderate (0.6 or -0.6).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Rear Leg</th>
<th>Front Leg</th>
<th>(d)</th>
<th>CI -</th>
<th>CI +</th>
<th>Inference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ankle angle at start</td>
<td>-7.9 ± 6.9</td>
<td>-2.5 ± 7.3</td>
<td>0.72</td>
<td>0.40</td>
<td>1.05</td>
<td>Possibly</td>
</tr>
<tr>
<td>Peak dorsiflexion angle</td>
<td>-14.1 ± 5.3</td>
<td>-12.7 ± 3.9</td>
<td>0.30</td>
<td>-0.12</td>
<td>0.71</td>
<td>Not Different</td>
</tr>
<tr>
<td>Peak plantarflexion angle</td>
<td>23.0 ± 3.7</td>
<td>37.8 ± 6.1</td>
<td>2.80</td>
<td>2.37</td>
<td>3.23</td>
<td>Almost Certain</td>
</tr>
<tr>
<td>Dorsiflexion ROM</td>
<td>-6.2 ± 3.4</td>
<td>-10.1 ± 4.3</td>
<td>-0.95</td>
<td>-1.52</td>
<td>-0.38</td>
<td>Likely</td>
</tr>
<tr>
<td>Plantarflexion ROM</td>
<td>37.1 ± 6.1</td>
<td>48.7 ± 5.5</td>
<td>1.91</td>
<td>1.54</td>
<td>2.29</td>
<td>Almost Certain</td>
</tr>
<tr>
<td>Knee angle at start</td>
<td>-54.4 ± 11.1</td>
<td>-80.8 ± 10.7</td>
<td>-2.30</td>
<td>-2.56</td>
<td>-2.05</td>
<td>Almost Certain</td>
</tr>
<tr>
<td>Knee peak extension angle</td>
<td>-39.0 ± 9.9</td>
<td>-10.5 ± 4.4</td>
<td>3.54</td>
<td>3.01</td>
<td>4.07</td>
<td>Almost Certain</td>
</tr>
<tr>
<td>Knee extension ROM</td>
<td>15.9 ± 7.2</td>
<td>72.4 ± 10.5</td>
<td>5.99</td>
<td>5.58</td>
<td>6.40</td>
<td>Almost Certain</td>
</tr>
<tr>
<td>Hip angle at start</td>
<td>-58.9 ± 8.1</td>
<td>-91.4 ± 9.2</td>
<td>-3.57</td>
<td>-3.34</td>
<td>-3.34</td>
<td>Almost Certain</td>
</tr>
<tr>
<td>Hip peak extension angle</td>
<td>-29.7 ± 6.5</td>
<td>12.0 ± 5.1</td>
<td>6.84</td>
<td>7.18</td>
<td>7.18</td>
<td>Almost Certain</td>
</tr>
<tr>
<td>Hip Extension ROM</td>
<td>29.9 ± 6.2</td>
<td>103.1 ± 5.6</td>
<td>11.80</td>
<td>11.45</td>
<td>12.15</td>
<td>Almost Certain</td>
</tr>
</tbody>
</table>

Joint angle, angular velocity, moment and power time histories for the ankle, knee and hip joint during the rear block and front block phases are presented in Figures 3.7-3.10. In both the rear and front leg, the ankle joint exhibited an initial period of dorsiflexion followed by plantarflexion (Fig. 3.7) and a net plantarflexion moment (Fig. 3.9) leading to energy absorption (Fig. 3.10, A1) followed by generation (Fig. 3.10, A2). A small extensor moment at the rear knee joint lead to minimal extensor energy generation, whereas there were clear and larger periods of extensor energy generation at the front knee joint (Fig. 3.10, K1). Extensor moments at the hip joint dominated the majority of the rear and front block phases (Fig. 3.9) leading to clear periods of energy generation (Fig. 3.10, H1) whilst the hip joint was extending (Fig. 3.8). As the hip joint attained maximal extension angular velocity in the front leg (Fig. 3.8) the resultant hip moment was flexor (Fig. 3.9) and thus a clear period of energy absorption (Fig. 3.10, H2) was evident. A proximal-distal pattern of the timing of peak joint powers was observed in the front leg but was absent in the rear leg, in which a knee-hip-ankle pattern was identified (Fig. 3.10).
Figure 3.7. Group ensemble average (solid line) and standard deviation (dotted line) flexion-extension joint angle-time histories for the ankle (top row), knee (middle row) and hip (bottom row) joint during the rear block (left column) and front block (right column) phase. Grey shaded area highlights the standard deviation of the end of the rear block phase.
Figure 3.8. Group ensemble average (solid line) and standard deviation (dotted line) flexion-extension joint angular velocity-time histories for the ankle (top row), knee (middle row) and hip (bottom row) joint during the rear block (left column) and front block (right column) phase. Grey shaded area highlights the standard deviation of the end of the rear block phase.
Figure 3.9. Group ensemble average (solid line) and standard deviation (dotted line) normalised joint moment-time histories for the ankle (top row), knee (middle row) and hip (bottom row) joint during the rear block (left column) and front block (right column) phase. Grey shaded area highlights the standard deviation of the end of the rear block phase.
Figure 3.10. Group ensemble average (solid line) and standard deviation (dotted line) normalised joint power-time histories for the ankle (top row), knee (middle row) and hip (bottom row) joint during the rear block (left column) and front block (right column) phase. Grey shaded area highlights the standard deviation of the end of the rear block phase.
Between-block comparisons revealed many meaningful joint kinetic differences that are summarised in Table 3.4. Typically, the very likely and almost certain differences were for positive effect sizes, indicating greater magnitudes in the front leg. However, peak ankle joint moment was the only variable greater in the rear leg that was deemed meaningful ($d = -1.59$, almost certain). During ankle joint extension (A2), peak power and positive work were almost certainly greater in the front leg, although average positive power was not different showing disparity between different variables from the same signal (Table 3.4).

At the knee joint, magnitudes of peak and average extensor moment, peak and average positive extensor power, and positive extensor work were almost certainly greater in the front leg compared with the rear ($d = 2.54$ to $3.82$). Although peak hip extension moment was only possibly greater for the front leg ($0.336 \pm 0.034$ vs. $0.288 \pm 0.069$, $d = 0.84$) all other kinetic variables were either very likely or almost certainly greater with the largest difference found between front ($0.307 \pm 0.045$) and rear ($0.090 \pm 0.032$) positive extensor work ($d = 5.31$).

The relative contribution of the hip joint to total leg extensor energy generation remained similar between the front ($58 \pm 8\%$) and rear ($57 \pm 10\%$) block and was the dominant contributor. The negligible contribution of the rear knee joint ($6 \pm 6\%$) meant that front knee joint $W_{\text{REL}}$ was almost certainly greater in the front block ($27 \pm 8\%$), and that ankle joint $W_{\text{REL}}$ was almost certainly greater in the rear leg ($37 \pm 7\%$) compared with the front ($15 \pm 2\%$) (Table 3.4).
Table 3.4. Front and rear leg joint kinetic data (mean ± SD). Standardised effect size ($d$) and 90% confidence intervals for between block comparisons are shown. Inferences are based on the likelihood of the true value of $d$ being moderate (0.6 or -0.6).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Rear Leg</th>
<th>Front Leg</th>
<th>$d$</th>
<th>CI -</th>
<th>CI +</th>
<th>Inference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak ankle extension moment</td>
<td>0.221 ± 0.035</td>
<td>0.167 ± 0.028</td>
<td>-1.59</td>
<td>-2.14</td>
<td>-1.05</td>
<td>Almost Certain</td>
</tr>
<tr>
<td>Peak knee extension moment</td>
<td>0.059 ± 0.032</td>
<td>0.226 ± 0.057</td>
<td>3.42</td>
<td>2.90</td>
<td>3.94</td>
<td>Almost Certain</td>
</tr>
<tr>
<td>Peak hip extension moment</td>
<td>0.288 ± 0.069</td>
<td>0.336 ± 0.034</td>
<td>0.84</td>
<td>0.21</td>
<td>1.47</td>
<td>Possibly</td>
</tr>
<tr>
<td>Peak negative ankle power</td>
<td>-0.076 ± 0.040</td>
<td>-0.057 ± 0.014</td>
<td>0.60</td>
<td>0.10</td>
<td>1.10</td>
<td>Possibly</td>
</tr>
<tr>
<td>Peak positive ankle power</td>
<td>0.253 ± 0.067</td>
<td>0.379 ± 0.093</td>
<td>1.48</td>
<td>1.00</td>
<td>1.97</td>
<td>Almost Certain</td>
</tr>
<tr>
<td>Peak positive knee power</td>
<td>0.053 ± 0.042</td>
<td>0.514 ± 0.167</td>
<td>3.61</td>
<td>3.09</td>
<td>4.12</td>
<td>Almost Certain</td>
</tr>
<tr>
<td>Peak positive hip power</td>
<td>0.381 ± 0.121</td>
<td>0.554 ± 0.064</td>
<td>1.70</td>
<td>1.12</td>
<td>2.28</td>
<td>Almost Certain</td>
</tr>
<tr>
<td>Average ankle extension moment</td>
<td>N/A</td>
<td>-0.440 ± 0.163</td>
<td>-0.01</td>
<td>-0.58</td>
<td>0.55</td>
<td>Not Different</td>
</tr>
<tr>
<td>Average knee extension moment</td>
<td>0.099 ± 0.019</td>
<td>0.099 ± 0.014</td>
<td>-0.01</td>
<td>-0.58</td>
<td>0.55</td>
<td>Not Different</td>
</tr>
<tr>
<td>Average hip extension moment</td>
<td>0.038 ± 0.024</td>
<td>0.126 ± 0.040</td>
<td>2.54</td>
<td>1.98</td>
<td>3.09</td>
<td>Almost Certain</td>
</tr>
<tr>
<td>Average negative ankle power (A1)</td>
<td>0.153 ± 0.037</td>
<td>0.202 ± 0.025</td>
<td>1.46</td>
<td>0.89</td>
<td>2.04</td>
<td>Very Likely</td>
</tr>
<tr>
<td>Average positive ankle power (A1)</td>
<td>-0.030 ± 0.016</td>
<td>-0.020 ± 0.008</td>
<td>0.81</td>
<td>0.20</td>
<td>1.41</td>
<td>Possibly</td>
</tr>
<tr>
<td>Average positive knee power (K1)</td>
<td>0.155 ± 0.036</td>
<td>0.145 ± 0.031</td>
<td>-0.30</td>
<td>-0.73</td>
<td>0.13</td>
<td>Not Different</td>
</tr>
<tr>
<td>Average positive hip power (H1)</td>
<td>0.022 ± 0.018</td>
<td>0.192 ± 0.069</td>
<td>3.20</td>
<td>2.65</td>
<td>3.75</td>
<td>Almost Certain</td>
</tr>
<tr>
<td>Average negative hip power (H2)</td>
<td>0.177 ± 0.056</td>
<td>0.304 ± 0.034</td>
<td>2.62</td>
<td>2.09</td>
<td>3.15</td>
<td>Almost Certain</td>
</tr>
<tr>
<td>Negative ankle work (A1)</td>
<td>N/A</td>
<td>-0.246 ± 0.097</td>
<td>-0.01</td>
<td>-1.16</td>
<td>0.05</td>
<td>Possibly</td>
</tr>
<tr>
<td>Positive ankle work (A2)</td>
<td>-0.008 ± 0.005</td>
<td>-0.012 ± 0.006</td>
<td>-0.56</td>
<td>-1.16</td>
<td>0.05</td>
<td>Possibly</td>
</tr>
<tr>
<td>Positive knee work (K1)</td>
<td>0.057 ± 0.015</td>
<td>0.081 ± 0.014</td>
<td>1.58</td>
<td>1.15</td>
<td>2.01</td>
<td>Almost Certain</td>
</tr>
<tr>
<td>Positive hip work (H1)</td>
<td>0.009 ± 0.011</td>
<td>0.144 ± 0.046</td>
<td>3.82</td>
<td>3.32</td>
<td>4.32</td>
<td>Almost Certain</td>
</tr>
<tr>
<td>Negative hip work (H2)</td>
<td>N/A</td>
<td>-0.043 ± 0.032</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.4 Theme 1 Discussion: **Biomechanics of the Block Start**

The aim of theme 1 was to investigate and quantify the biomechanical demand of executing the block start. In order to answer research questions 1 to 4, contributing to an improved understanding of block start biomechanics, a cross sectional analysis of the block start was undertaken with 17 national and international level sprinters with external force and 3D motion data collected. This permitted the calculation of external kinetic data, and lower limb joint kinematic and kinetic data in order to quantify the biomechanical demand of executing the block start. Results showed a distinct difference in the pattern of external force and power in the block start, and key joint level findings highlighted the asymmetrical nature of the block
start was most pertinent at the knee joint, and that leg extensor energy was predominantly generated at the hip joint.

3.4.1 External Kinetics
When converted into N.kg\(^{-1}\) the magnitude of peak resultant forces in the front (16.33 ± 1.95 N.kg\(^{-1}\)) and rear (15.34 ± 1.91 N.kg\(^{-1}\)) block were comparable with those reported by Willwacher, Herrmann, Heinrich et al., (2013) utilising the same instrumented starting blocks with elite male sprinters with 100 m personal best times of 10.06 ± 0.28 s (16.27 ± 2.64 and 15.98 ± 2.57, respectively). Similar peak resultant forces (16.18 ± 2.27 and 15.41 ± 2.04, respectively) were also reported in a group of 19 male sprinters with personal best times similar to the present group (10.54 ± 0.54 s), again when utilising instrumented starting blocks (Willwacher et al., 2016). The agreement between these studies confirms that the data collected are representative of similar sprint athlete populations.

The magnitude of peak horizontal and vertical force was superior in the rear block and front block, respectively (Table 3.2), leading to small and possibly greater peak resultant forces in the front block. Previously it has been established that more accomplished sprinters exhibit more balanced front and rear peak resultant forces (Willwacher, Herrmann, Heinrich et al., 2013), however understanding that these similar resultant forces come from differing magnitudes of horizontal and vertical force is valuable when seeking to understand the mechanical role of each leg. The very likely and almost certainly greater magnitude of peak and average $F_Z$ in the front block (Table 3.2) may be explained by the demand placed on the front leg to support the athlete’s body mass when the block phase becomes unilateral. Additionally, large magnitudes of $F_Y$ generated in the rear block when both legs are pushing in the blocks may reduce the time taken to rotate the centre of mass about the front leg so that extension of the front leg can maximally contribute towards horizontal motion of the sprinter (Jacobs & van Ingen Schenau, 1992).

The pattern of external force production presented in Figure 3.6 is similar to that described by Otsuka et al. (2014) and Willwacher et al. (2016) with a steep rise to peak rear block $F_Y$ whilst a double peak in front block $F_Y$ can be observed. The latency period in front $F_Y$ as the magnitude of force applied to the rear block
decreases again may be a result of the increase in demand to support body weight during this period of switching between bilateral and unilateral support. Once the rear leg had left the block, front $F_Y$ began to increase again to its global maximum at approximately 80% of block time (Fig. 3.6).

Average horizontal force was only found to be possibly different between the front and rear block (Table 3.2). Therefore, whilst peak horizontal forces favoured the rear block, the different characteristics of horizontal force production between the front and rear block meant that over their respective phases the average horizontal force generated was similar. Again when normalised only to body mass, average $F_Y$ data in the present study ($5.58 \pm 0.71$ and $6.01 \pm 0.52$) was comparable with that of Otsuka et al. (2014) who reported values of $6.70 \pm 0.58$ and $5.82 \pm 0.71$ for the front and rear block, respectively, in a sample of nine well trained Japanese sprinters (100 m PB, $10.87 \pm 0.41$ s).

Interestingly, the pattern of external force and power generation in the block phase were opposite in nature (Fig. 3.6). A double peak nature emerged for both total $F_Y$ and $P_Y$, but their magnitudes were in reverse, with global peak $F_Y$ occurring during the bilateral portion of the block start and global peak $P_Y$ occurring only when the front leg was in contact (Fig. 3.6). Therefore, it appears that the initial amount of total horizontal force produced by both legs (but mainly the rear) is required to initiate horizontal velocity of the centre of mass. Once this has been achieved, horizontal force produced solely in the front block is responsible for the second and larger of the two external power peaks. The nature of external power generation means that for a similar magnitude of force input, the front block can contribute a greater degree towards total external power because of the increased horizontal velocity of the centre of mass.

3.4.2 Joint Kinematics & Kinetics

In agreement with previous research (Bezodis et al., 2015; Harland & Steele, 1997), the hip and knee joint in the front leg were placed in a greater magnitude of flexion in the set position (Table 3.3). On average, these differences were approximately $25^\circ$ and $30^\circ$ at the knee and hip, respectively, which is in agreement with the approximate $23^\circ$ and $30^\circ$ differences reported by Bezodis et al. (2015).
large between-athlete variability in ankle angle in the set position, only a possible difference existed in favour of the rear ankle being in greater flexion (Table 3.3). However, on average both ankle joints were posed in less than 10° of dorsiflexion and were thus in a neutral position. Once the block phase had commenced, a pattern of dorsiflexion-plantarflexion emerged at the ankle joint (Fig. 3.7-3.8), by which the front ankle underwent a likely \(d = -0.95\) and almost certainly \(d = 1.91\) greater range of dorsiflexion and plantarflexion, respectively. At the hip, joint both legs extended for almost the entirety of the block phase (Fig. 3.7-3.8) with an almost certainly greater range of extension at the front leg (29.9 ± 6.2 vs. 103.1 ± 5.6, \(d = 11.80\)). This was in part a result of the differences in the set position but also the peak extension angle, which was still in a state of flexion in the rear leg (-29.7 ± 6.5) but hyperextended in the front (12.0 ± 5.1) (Table 3.3).

At the knee joint there were more clear differences in the nature of joint motion between the front and rear leg (Fig. 3.7-3.8). At the rear leg, the knee joint began to extend with the initiation of the block phase and overall extended through a small (15.9 ± 7.2) range of motion. Following this, between 60 and 90% of rear block time, the knee joint began to flex prior to leaving the block. The observed flexion at the rear knee may be a strategy to lower the inertia of the rear leg in preparation for swing, to ensure repositioning of the rear leg in minimal time ready for first stance touchdown. At the front knee joint, extension was minimal for the first 40% of block time before rapidly extending through an approximate 70° range of motion prior to block exit.

Front and rear leg ankle joint kinetic patterns were similar to what has previously been shown in the block phase (Mero et al., 2006) and first stance after block exit (Bezodis et al., 2014), by showing a constant plantarflexion moment whilst undergoing a flexion-extension pattern, resulting in a period of extensor energy absorption followed by generation. This data is indicative of an eccentric-concentric loading of the plantarflexors and therefore stretch-shortening action (Mero et al., 2006; Slawinski, Bonnefoy, Ontanon et al., 2010). Whilst peak ankle extensor moment was almost certainly greater in the rear block (0.221 ± 0.035 vs. 0.167 ± 0.028, \(d = -1.59\)), average extensor moment was not different (0.099 ± 0.019 vs. 0.099 ± 0.014, \(d = -0.01\)). The different interpretation from these data justified the
Possibly greater peak and average negative power in phase A1 were observed in the rear block (Table 3.4) and appeared to be a result of larger extensor moments during phase A1 and not differences in flexion angular velocity (Fig. 3.8-3.9). However, the overall work done in this phase favoured the front leg (-0.012 ± 0.006 vs. -0.008 ± 0.005, \(d = -0.56\), possibly) and could be attributed to the longer absolute duration of phase A1. Peak positive ankle power (0.379 ± 0.093) and work (0.081 ± 0.014) were almost certainly greater in the front block compared with the rear (0.253 ± 0.067 and 0.057 ± 0.015, respectively). The lower magnitude of positive ankle power and work in the rear block may be due to the absence of a proximal-distal strategy of power generation, decreasing the amount of energy that could be liberated from the knee joint to assist with ankle plantarflexion (Jacobs, Bobbert, & van Ingen Schenau, 1996).

Almost certainly lower magnitudes of extensor moment, power and work were observed at the rear knee joint compared with the front during the block phase (Table 3.4), and a distinct difference in the pattern of kinematics and kinetics were observed (Fig. 3.7-3.10). Although some differences in discrete kinetic variables were also observed at the ankle and hip joint between the front and rear leg, temporal patterns were similar between legs, indicating that the primary source of asymmetry in the block phase was at the knee joint. A low rear knee moment for the first 80% of the rear block phase may have indicated a specific role of the rear knee joint to stabilise the lower limb and facilitate the large forces generated at the hip and ankle being effectively applied to the block. This specific technique appeared to result from a low moment arm caused by the orientation of the resultant force vector with respect to the knee joint location, a potential constraint of the starting blocks placing the rear leg into a more extended position.

Front knee joint peak power (0.514 ± 0.167) was almost 10 times greater than the rear (0.053 ± 0.042), and front knee joint positive extensor work done in phase K1 (0.144 ± 0.046) was more than 15 times greater than the rear (0.009 ± 0.011). These data confirmed the important energy generating role of the joint (albeit the front leg)
during the sprint start (Bezodis et al., 2014; Debaere et al., 2013), and the much greater musculoskeletal demand at the front knee joint when executing the block start. A proximal-distal pattern of peak joint powers was evident in the front block and is a strategy often adopted in power demanding tasks (Jacobs et al., 1996). Inherent with this strategy during sprint acceleration is delayed active extension at the knee and ankle joints until the CM has been sufficiently rotated in front of the foot in order to maximise forward propulsion (Jacobs & van Ingen Schenau, 1992). Whilst commonly described during stance (Bezodis et al., 2014; Debaere et al., 2013), results of the present study indicated that this also occurred in the block phase, with the main periods of positive extensor power at the front ankle and knee joints occurring after the rear foot had left the blocks (Fig. 3.10).

Peak and average hip joint extension moment were deemed possibly and very likely greater in the front block, respectively (Table 3.4). The increase in likelihood between variables may be explained by the nature of the moment profiles, with a greater rate of decline in hip extensor joint moment at the rear leg, following the initial maxima, compared with the front leg (Fig. 3.9). All variables encompassing hip joint positive extensor power were shown to be almost certainly greater in the front leg, with large to extremely large effect sizes observed for peak positive power ($d = 1.70$), average positive power ($d = 2.62$), and positive work ($d = 5.31$). Higher magnitudes of extensor moment and extension angular velocity at the point of peak power, accompanied by a shallower decrease in extensor moment at the front leg, explained the observed difference in hip joint extensor power data. In addition, the absolute duration of phase H1 was longer in the front block and contributed to the observed differences in positive work. Overall, it can be suggested that the kinetic demand of extending the hip joint was greater in the front leg compared with the rear when executing the block phase.

The calculation of relative work ($W_{REL}$) permitted the contribution of each joint to total leg extensor energy generation to be quantified and provided insight into the major generators of leg extensor energy for both legs during the block start. Results highlighted large $W_{REL}$ at the hip joint (rear, $57 \pm 10\%$; front, $58 \pm 8\%$, Table 3.4), supporting the importance of the hip joint for block phase execution (Bezodis et al., 2015; Mero et al., 2006; Slawinski, Bonnefoy, Ontanon et al., 2010). Due to the small
and almost certainly lower energy generating role of the rear knee joint (6 ± 6%) compared with the front leg (27 ± 8%), the contribution of the rear ankle joint was almost certainly greater in the rear leg (37 ± 7%) compared with the front leg (15 ± 2%). Therefore, whilst the magnitude of positive extensor work at all lower limb joints were almost certainly greater in the front leg (Table 3.4), the relative musculoskeletal demand between each leg was similar at the hip joint, higher at the ankle joint in the rear leg and higher at the knee joint in the front leg.

Previous research has identified the ankle joint as the main contributor toward centre of mass acceleration in the first two stance phases following block clearance (Debaere, Delecluse, Aerenhouts, Hagman, & Jonkers, 2015), disagreeing with the findings of the current study. However, the study by Debaere et al. (2015) utilised induced acceleration techniques to quantify each joints contribution to horizontal and vertical propulsion, differing from the calculation of \( W_{\text{REL}} \) in the current study. Although induced acceleration was not used in this study, the dominance of hip extensor energy generation may be explained by the block phase beginning from a stationary position, placing high demand on the powerful hip extensors to initiate motion.

Overall, \( W_{\text{REL}} \) indicated the large energy generating role of the ankle, knee and hip joint that was distributed across both legs during the block start. The importance of ensuring high strength and power capacity of the hip and knee extensor and plantarflexor musculature was therefore apparent. However, the temporal organisation of joint powers (Fig. 3.10) suggests that simply improving the strength and power capacity at each joint may not translate into performance improvements, and promoting coordination specificity in strength training exercises may enhance the positive transfer to increased block start performance (Bobbert & van Soest, 1994). The quantification of \( W_{\text{REL}} \) in future biomechanics studies could have many applications, including the identification of athletes being ankle, knee, or hip dominant when executing particular tasks.

3.4.3 Theme 1 Conclusion
In the introduction to this chapter, two key questions were identified that can be addressed following the investigation carried out in Theme 1:
**Research Question 1** – What are the external kinetic and lower limb joint kinematic and kinetic characteristics of block start technique?

The present study revealed that total external force and power generated in the block phase both exhibited a double-peak pattern but were dissimilar in nature and the relative contribution from the front and rear block. Joint kinematic data revealed a flexion-extension pattern at both ankle joints, an extension pattern at both hip joints and the front knee, and an extension-flexion pattern at the rear knee. Ankle joint moments were extensor throughout and resulted in periods of extensor energy absorption and generation. The resultant joint moment at the rear knee was of small magnitude for the majority of the rear block phase but were large and extensor in the front leg in which a distinct period of extensor energy generation commenced at approximately 50% of block time. At the hip joint, moments were large and extensor for the majority of each legs respective phase and contributed to almost 60% of the total extensor energy generation for each leg. A specific organisation of joint kinematics and kinetics existed in the front leg to facilitate the generation of horizontal power, by which extension of the front knee and ankle were delayed until later in the block phase.

**Research Question 2** – How are the biomechanics of the block start different between the front and rear block / leg?

In order to answer this question, standardised effect sizes were calculated between the front and rear leg and inferences were made based on the 90% confidence intervals of the effect size and the percentage likelihood of the true effect being at least moderate ($d = \pm 0.6$). Key findings highlighted that greater vertical force was produced in the front block whereas peak horizontal force was likely greater in the rear block. Peak and average horizontal power was almost certainly greater at the front block when comparing the contribution of horizontal force production in each block to total power of the centre of mass.

At the joint level, greater extensor range of motion and an overall greater extensor musculoskeletal demand was identified at the front leg. Increased musculoskeletal demand at the front leg was most apparent at the joint power level, as almost certainly greater peak and average positive extensor power, and positive extensor work was typically demonstrated across the front leg lower limb joints. Key
differences in knee joint kinematic and kinetic profiles and discrete data indicated that this was the primary source of technique asymmetry in the block start, with the rear knee only contributing towards 6% of all extensor energy generation at the rear leg, compared with 27% in the front leg.

3.4.4 Theme 1 Summary
By investigating the external kinetic, joint kinematic and joint kinetic characteristics of block start technique, the purpose of this section was to provide a deeper holistic understanding of block start biomechanics. Amongst the detailing of these biomechanical data, novel information emerged in the joint kinetic analysis by comparing the musculoskeletal demand between the front and rear leg. A large demand was placed on the musculature surrounding the hip joint in order to generate large amounts of extensor energy, almost 60% of that generated by all three lower limb joints. Disparity in the energy generating role of the front and rear knee highlighted that a specific role of the rear knee may exist to facilitate the large forces generated at the hip and ankle being effectively applied to the rear block. Delayed powerful extension of the front knee and ankle joints emerged from the current data, recognising a task-specific strategy to ensure maximal contribution of the extension on these joints to horizontal motion of the sprinter’s centre of mass.

In continuation of Theme 1, the second theme sought to elucidate the key determinants of performance from both an external and joint kinetic perspective. The purpose of Theme 2 was to understand which variables are associated with superior performance, in order to aid mechanical underpinning of the block start and the relevance of strength training to target the biomechanical determinants of performance (Chapter 5). In advance of Theme 2 results, extensor moment and positive extensor power data are to be represented by capital letters M and P, and subscript \text{ANK}, \text{KNE}, and \text{HIP} have been used to represent the ankle, knee and hip joint, respectively.
3.5 Theme 2 Results: Biomechanical Determinants of Block Start Performance

3.5.1 External Kinetics

Front and rear block peak $F_Y$ was found to be very likely ($r = 0.57$) and likely ($r = 0.41$) positively associated with block performance. Likely positive relationships ($r = 0.46$ and $r = 0.44$) were found for front and rear average $F_Y$, respectively, and regression analysis revealed that 86% of the variation in NAHP was explained by front and rear average $F_Y$ (Table 3.5). Within the regression model, standardised coefficients (0.964 and 0.951) and squared part correlations (0.66 and 0.65) were similar for the front and rear block, respectively.

Table 3.5. External kinetic regression model for starting block performance (NAHP).

<table>
<thead>
<tr>
<th>Model</th>
<th>Coefficients</th>
<th>95% confidence intervals</th>
<th>Standardised Coefficients</th>
<th>Part$^2$</th>
<th>DW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dependent: NAHP</td>
<td>Con. -0.244</td>
<td>-0.430 – -0.059</td>
<td></td>
<td></td>
<td>2.790</td>
</tr>
<tr>
<td>Independent(s):</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Front average $F_Y$</td>
<td>0.758</td>
<td>0.555 – 0.961</td>
<td>0.964</td>
<td>0.66</td>
<td></td>
</tr>
<tr>
<td>Rear average $F_Y$</td>
<td>0.527</td>
<td>0.384 – 0.670</td>
<td>0.951</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td>$R^2$ Adj. = 0.84</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


3.5.2 Joint Kinetics

The correlation values between internal (joint moment and power) and external (average $F_Y$ and NAHP) kinetics for the rear and front block are presented in Figures 3.11 and 3.12, respectively. Almost certain positive relationships with rear $F_Y$ were found for peak and average $M_{ANK}$ ($r = 0.71$ and 0.83, respectively), $M_{HIP}$ ($r = 0.68$ and 0.80, respectively) and average $P_{HIP}$ ($r = 0.73$). Peak $P_{HIP}$ was very likely associated with $F_Y$ ($r = 0.55$). For the front block, peak and average $M_{ANK}$ was almost certainly related to $F_Y$ ($r = 0.74$ and 0.83, respectively), whilst peak and average $M_{KNE}$ ($r = 0.55$ and 0.63) were very likely related to $F_Y$. At the front hip joint, peak ($r = 0.57$) and average ($r = 0.43$) $M_{HIP}$ were very likely and likely related to $F_Y$, respectively.
The strongest positive relationships between front leg joint power and front \( F_Y \) were identified at the knee joint and were classed as very likely (\( r = 0.56 \) and 0.57, for peak and average \( P_{\text{KNE}} \), respectively). When assessing relationships with NAHP (Fig. 3.11-3.12) only one variable possessed at least a very likely positive correlation and was observed for front leg peak \( P_{\text{KNE}} \) (\( r = 0.55 \)). In the rear leg, likely positive relationships with NAHP were found for the ankle joint (peak \( M_{\text{ANK}} \) \( r = 0.36 \); average \( M_{\text{ANK}} \) \( r = 0.39 \)). Many other likely positive correlations were found between front leg joint kinetic variables and NAHP (\( r = 0.35 \) to 0.46, Fig. 3.12), with only peak \( P_{\text{HIP}} \) (\( r = 0.16 \)) and average \( M_{\text{KNE}} \) (\( r = 0.24 \)) classified as unclear.
Figure 3.11. Pearson correlation coefficients (± 90% CI) between rear leg joint kinetic data and rear block average horizontal force (rear $F_Y$) and starting block performance (NAHP). Central area ($r = -0.1$ to $0.1$) indicates a trivial relationship. Marker colour indicates unclear (grey outline), likely (grey fill), very likely (black outline), and almost certain (black fill) relationships.
Figure 3.12. Pearson correlation coefficients (± 90% CI) between front leg joint kinetic data and front block average horizontal force (rear $F_Y$) and starting block performance (NAHP). Central area ($r = -0.1$ to $0.1$) indicates a trivial relationship. Marker colour indicates unclear (grey outline), likely (grey fill), very likely (black outline), and almost certain (black fill) relationships.
Based on the bivariate correlations, 12 variables possessing a likely ($r \geq 0.33$) relationship with NAHP were used as independent variables in a stepwise multiple regression with NAHP as the dependent variable. The model that explained the greatest amount of variance in NAHP included three of the twelve variables (rear average M\text{ANK}, front average M\text{HIP} and front peak P\text{KNE}) and possessed an $R^2$ of 0.60 (Table 3.6). Normality of the residuals and homoscedasticity were confirmed, and autocorrelation was not present (Durbin-Watson = 1.512, upper limit ($n = 17$, $k = 3$) = 1.432). The following equation could thus be formed using the unstandardised coefficients, reflecting the lower limb joint kinetics of the current study:

$$NAHP = 0.253 + (0.111 \times \text{front peak P}\text{KNE}) + (0.972 \times \text{rear average M}\text{ANK}) + (0.606 \times \text{front average M}\text{HIP})$$

Assessing the squared part correlations for each predictor variable revealed that of the 60% total variance in NAHP explained by the regression model, 21%, 21% and 11% was uniquely explained by front peak P\text{KNE}, rear average M\text{ANK}, and front average M\text{HIP}, respectively. The remaining 7% of the variance was thus explained by shared variance amongst the predictors.

Table 3.6. Joint kinetic regression model for starting block performance (NAHP).

<table>
<thead>
<tr>
<th>Model</th>
<th>Coefficients</th>
<th>95% confidence intervals</th>
<th>Standardised Coefficients</th>
<th>Part$^2$</th>
<th>DW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dependent: NAHP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.512</td>
</tr>
<tr>
<td>Independent(s): Front peak P\text{KNE}</td>
<td>0.111</td>
<td>0.019 – 0.203</td>
<td>0.478</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>Rear average M\text{ANK}</td>
<td>0.972</td>
<td>0.166 – 1.779</td>
<td>0.457</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>Front average M\text{HIP}</td>
<td>0.606</td>
<td>-0.072 – 1.284</td>
<td>0.355</td>
<td>0.11</td>
<td></td>
</tr>
</tbody>
</table>

$R^2$ Adj = $R^2$ adjusted. Part$^2$ = part squared correlation. DW = Durbin-Watson statistic.
3.6 Theme 2 Discussion: *Biomechanical Determinants of Block Start Performance*

The aim of Theme 2 was to investigate the relationships between lower limb joint kinetics, external kinetics and overall block start performance. In order to answer the research questions contributing to an improved understanding of the variables associated with higher levels of block start performance, linear correlation and regression analyses were undertaken to explore the associations between lower limb joint kinetics, average $F_Y$ and starting block performance (NAHP). Key findings highlighted that 86% of the variation in block performance was explained by the horizontal force applied to the front and rear blocks. At the joint level, 60% of the variation in block performance was explained by the magnitude of rear ankle and front hip joint average extensor moment, and front knee joint peak positive extensor power.

The importance of maximising total average $F_Y$ to achieve higher levels of block start performance was confirmed (Willwacher et al., 2016), with NAHP sharing 86% of its variance with the magnitude of average horizontal force produced in the front and rear block (Table 3.5). Investigating standardised regression coefficients (0.964 and 0.951) and $\text{Part}^2$ correlations (0.66 and 0.65) (Table 3.5), it cannot be concluded that either front or rear average $F_Y$, respectively, had significantly greater predictive ability for NAHP. This is somewhat in agreement with Willwacher et al. (2016) who showed a tendency towards force application in the rear block being of greater importance for block performance but ultimately demonstrated the importance of high force application to both blocks. Therefore, from an external kinetic perspective, maximising total average horizontal force appears to be the key characteristic of successful block performance.

Interestingly, the sum of the front and rear $\text{Part}^2$ was greater than the model $R^2$ (Table 3.5), indicating a situation of cooperative suppression (Cohen, Cohen, West, & Aiken, 2003). In scenarios when cooperative suppression is present, the independent variables are mutually enhancing, by which each independent variable accounts for a larger proportion of variance of the dependent variable in the presence of the other, than it does alone (Cohen et al., 2003). Negative correlations between independent variables can lead to cooperative suppression, and in the current study a negative correlation was found between front and rear average $F_Y$ ($r = -0.53$). Therefore, a scenario by which a negative interaction between front and
rear horizontal force production may exist and therefore athletes may have individual preferences towards applying force on the rear or front block. Negative interactions in sprinting have also been identified for step length and frequency (Hunter, Marshall, & McNair, 2004a) with the existence of individual reliance (Salo, Bezodis, Batterham, & Kerwin, 2011) typically being attributed to different neuromuscular factors. From the current data it is difficult to elucidate the mechanisms underpinning individual preference for front or rear force production, although differences in set position and the neuromuscular capacity of each leg could be interesting avenues for future research. Further within-athlete investigations could help to clarify the possibility of individual preferences.

Given the importance of maximising average $F_Y$, highlighted in this investigation and others (Otsuka et al., 2014; Rabita et al., 2015; Willwacher et al., 2016), the next step was to explore the relationships between lower limb joint kinetics and average $F_Y$, in order to gain a deeper understanding of the strategies associated with increased external horizontal force production. Peak and average extensor joint moment and positive extensor joint power was used in this analysis because they explain lower limb extension, yet describe different characteristics of moment and power curves (Fig. 3.9-3.10).

For the rear block, both peak and average $M_{ANK}$ ($r = 0.71$ and $0.83$) and $M_{HIP}$ ($r = 0.68$ and $0.80$) were almost certainly positively related to average rear $F_Y$ (Fig. 3.11), and supported previous findings of the large role of the ankle and hip joint in generating force in the rear block (Mero et al., 2006). At the joint power level, correlation magnitudes decreased considerably at the ankle joint ($r = 0.32$ and $0.41$ for peak and average $P_{ANK}$, respectively), whilst peak and average $P_{HIP}$ remained very likely ($r = 0.55$) and almost certainly ($r = 0.73$) positively related to rear average $F_Y$. Therefore, generating high magnitudes of moment and power at the rear hip early in the block phase (Fig. 3.9-3.10) coupled with large ankle moments to effectively apply these forces into the rear block could be the determining characteristics of the magnitude of horizontal force generated in the rear block.

Correlation magnitudes were all larger when using average joint moment and power data compared with peak values, although the order of correlation strength between the rear ankle and hip joint was unaffected. Therefore, for the rear block, using peak or average data did not appear to affect the interpretation of results and probably
explain similar biomechanical demands. Rear knee joint kinetic data were excluded from the current analysis because of the low magnitude of extensor moment and power observed in Theme 1 (Fig. 3.9-3.10).

In the front block, correlation strength for average $M_{\text{ANK}}$ ($r = 0.83$, almost certain), $M_{\text{KNE}}$ ($r = 0.63$, very likely) and $M_{\text{HIP}}$ ($r = 0.43$, likely) with average $F_Y$ increased when moving from proximal to distal. Whilst hip joint moments were largest in magnitude for the front leg (Table 3.4), the temporal similarity between front $F_Y$, $M_{\text{ANK}}$ and $M_{\text{KNE}}$ may help explain why the more distal joints possessed stronger relationships with the magnitude of horizontal force applied to the front block (Fig. 3.6, 3.9). Furthermore, because the ankle is the most distal joint in the kinetic chain, it may have a larger influence on the application of force onto the block, and regulate the horizontal orientation of resultant external forces (Rabita et al., 2015). However, when looking at peak values, $M_{\text{HIP}}$ was very likely related to average $F_Y$ ($r = 0.57$). Therefore, although there was a distinct superiority in correlation strength for the ankle joint, certain variables reflecting moment data at the knee and hip were still very likely related to front $F_Y$. Thus, there was not one particular joint in the front leg that entirely explained the between-athlete variability in front block average horizontal force.

At the joint power level, the knee was the only joint that possessed a very likely positive relationship with front average $F_Y$ ($r = 0.56$ and 0.57 for peak and average $P_{\text{KNE}}$, respectively). Thus, although all joint moments appeared important when determining front average $F_Y$, it was the ability to organise powerful extension at the knee joint that was found to be most strongly related to the magnitude of horizontal force applied to the front block. With respect to strength and power development, exercises that elicit large moments at the ankle, knee and hip joint, whilst emphasising knee joint power production during triple extension would overload the specific musculoskeletal demand of the block start to achieve physiological adaptations that can result in improved performance (Irwin et al., 2007; Matveyev, 1981; Moir et al., 2018).

Whilst the previous data has provided information relating to the joint kinetic determinants of horizontal force applied to the front and rear block, it was of further interest to investigate whether these relationships extended to overall starting block performance. This investigation was exploratory in nature because it was already
established that there were clearly different individual strategies with respect to front
and rear $F_Y$ but together they explain 86% of the variation in NAHP (Table 3.5).
Furthermore, Figure 3.6 showed that horizontal external force and power follow a
different temporal pattern and therefore joint kinetic data in the front block may hold
greater predictive ability of NAHP. Figures 3.9 and 3.10 supported this notion by
highlighting that two rear leg but ten front leg joint kinetic variables possessed at
least a likely positive relationship with NAHP ($r = 0.35$ to 0.55).

When evaluating the individual bivariate correlations, the strongest and only very
likely positive relationship with NAHP was found for front knee peak power ($r = 0.55$).
This supported the data in Figure 3.10 that highlighted large between-athlete
variation in front knee extensor power generation. Furthermore, the instance of peak
knee power (Fig. 3.10) was aligned temporally with that of peak external power (Fig.
3.6) indicating that the very likely association between peak front $P_{\text{KNE}}$ and NAHP
could have been a result of its mechanical link with peak external power. Many likely
positive relationships existed between joint kinetic variables and block performance,
but only two existed for the rear leg, which were the two variables encompassing
extensor moment properties at the rear ankle joint ($r = 0.36$ and 0.39 for peak and
average $M_{\text{ANK}}$, respectively) (Fig. 3.11). Therefore, whilst rear hip moment and
power were key determinants of rear block average $F_Y$, only rear ankle moment data
continued to possess a positive and meaningful relationship with block performance.

Understanding the key determinants of NAHP from front leg joint kinetic data was
difficult and complex when only considering the bivariate relationships, as there
were many likely positive relationships with a small range of $r$-values (0.35 to 0.46).
Generally, the correlation magnitudes between peak and average data were in
agreement, although this was not the case for $P_{\text{HIP}}$. Whilst peak $P_{\text{HIP}}$ possessed an
unclear relationship with NAHP, average $P_{\text{HIP}}$ was likely positively correlated ($r =
0.39$). The importance of maintaining high power at the hip joint appeared to be
more critical to performance than simply maximising the peak magnitude.

As a final step towards understanding the key determinants of block performance,
multiple regression analysis revealed that three variables (rear average $M_{\text{ANK}}$, front
average $M_{\text{HIP}}$ and front peak $P_{\text{KNE}}$) were able to explain 60% of the variation in NAHP
(Table 3.6), with 21%, 11% and 21% of the variation in NAHP being uniquely
explained by each predictor, respectively. The inclusion of average front hip moment
is in agreement with previous investigations that have detailed the importance of the hip joint when executing the block start (Bezodis et al., 2015; Mero et al., 2006; Slawinski, Bonnefoy, Ontanon et al., 2010). The identification of average extensor moment at the rear ankle joint, and peak positive extensor power at the front knee joint, as key determinants of block start performance, were novel additions in the current study to the block start literature.

It was not the case that those variables highly associated with rear or front average $F_Y$ (i.e. rear $M_{HIP}$ and $P_{HIP}$, and front $M_{ANK}$) were necessarily highly associated with NAHP and may again reflect the individual dominances in front and rear force application. However, results of the current regression analysis can be used to understand the main strategies required for successful starting block performance. Hip joint moment at the front leg are large and extensor for approximately 80% of the block phase (Fig. 3.9) and can have a considerable opportunity to influence block performance, whilst the main phase of front leg positive extensor knee power (Fig. 3.10) coincides temporally with peak external power (Fig. 3.6) and was shown to exhibit large between-athlete variability. High extensor moments at the rear ankle may reflect a neuromuscular characteristic of superior block performers to ensure resistance to dorsiflexion, providing a stiff ankle complex that assists the effective application of the large forces generated in minimal time (Cavagna, 1977; Guissard et al., 1992).

3.6.1 Theme 2 Conclusion
In the introduction to this chapter, two key questions were identified and can be addressed following the current analysis:

**Research Question 3 – Which external kinetic variables are associated with higher levels of block performance?**

Utilising multiple regression analysis, the current analysis highlighted that rear and front block average horizontal force accounted for 86% of the variance in block performance. The contribution of each to the regression model was similar ($\text{part}^2 = 0.66$ and 0.65 for front and rear, respectively), indicating equal importance to block performance and that the total magnitude of horizontal force was critical. A negative interaction existed between average front and rear $F_Y$ ($r = -0.53$) and highlighted
that athletes may have individual preferences towards favouring front or rear force production.

Research Question 4 – What are the relationships between lower limb joint kinetics, external kinetics and starting block performance?

Given the importance of maximising average horizontal force in both blocks, it was of interest to first understand the lower limb joint kinetic determinants of external force production. To achieve this, a combination of linear correlation and multiple regression techniques were utilised. When interpreting the strength of bivariate correlations, magnitude based inferences were made based on the percentage likelihood that the true relationship (using 90% confidence intervals) was greater than \( r = 0.1 \). Correlations revealed that in the rear block, average horizontal force was almost certainly related to rear leg ankle and hip joint extensor moment and hip joint positive extensor. In the front block, there were many positive and meaningful (at least likely) relationships between average \( F_Y \) and front leg joint moment data, although relationships were strongest for the ankle joint. However, at the joint power level the knee joint was established as the only joint to be very likely related to average \( F_Y \).

In total, twelve joint kinetic variables were meaningfully related to block performance. Of which, only two were identified at the rear leg, and only front peak possessed a ‘very likely’ magnitude. Multiple regression techniques revealed that rear ankle and front hip joint average extensor moment, and front knee joint peak positive power were the key joint kinetic determinants of block performance, accounting for 60% of the overall variation in NAHP.

3.6.2 Theme 2 Summary
By investigating the relationships between external kinetics, joint kinetics and block performance, the purpose of Theme 2 was to gain a greater understanding of the key variables associated with performance, so that future analysis of training exercises can be targeted towards variables that hold relevance to performance. Results confirmed the importance of ensuring high total average horizontal force and added novel information by identifying the joint kinetic variables that were associated with the magnitude of horizontal force applied to each block. In the rear block, variables reflecting extensor moment at the ankle and hip joint, and positive
extensor power at the hip joint were almost certainly related to average $F_Y$. In the front block, extensor moment variables at the ankle, knee and hip joint possessed at least a very likely positive association with average $F_Y$ although these were largest at the ankle joint. In addition, positive extensor power generation was only very likely associated with average $F_Y$ for the knee joint.

Multiple regression analysis highlighted that 60% of the variation in block performance was explained by average extensor moment at the rear ankle and front hip joint, and peak positive extensor power at the front knee joint. These three variables should be considered alongside the individual bivariate correlations, to comprehensively understand the lower limb joint kinetic strategies adopted by superior block performers.

### 3.7 Chapter Summary

This study has quantified the biomechanical demand of executing the block start through an investigation of external kinetics, joint kinematics and joint kinetics in 17 national and international male sprinters. Key results highlighted the dominant energy generating role of the hip joint towards overall leg extensor energy generation, that the front leg is subject to greater extensor musculoskeletal demand, and that the asymmetrical nature of the block phase was most evident at the knee joint. When seeking to understand the kinetic determinants of block performance, it was observed that maximising total average horizontal force was the key strategy adopted by superior block performers.

At the joint level, those variables highly associated with the magnitude of horizontal force generated in each block were not necessarily those that possessed the strongest relationship with block performance and appeared to be a result of between-athlete reliance on either front or rear block force production. Three joint variables, average extensor moment at the rear ankle and front hip joint and peak positive extensor power at the front knee joint, were able to account for 60% of the total variance in block performance and were revealed as the key lower limb joint kinetic determinants of block performance. However, a remaining 40% of unexplained variance, coupled with similar bivariate correlation magnitudes argue that block performance is complex and that investigating the interaction amongst the lower limb joints requires further analysis.
CHAPTER 4. AN INTRA-LIMB JOINT COORDINATION AND COORDINATION VARIABILITY ANALYSIS OF BLOCK START TECHNIQUE

4.1 Introduction
In Chapter 2, it was recognised that similarity in movement pattern is a key factor influencing the efficacy of a particular exercise to elicit positive training transfer and enhance performance of a competitive motor task (Bobbert & Van Soest, 1994; Siff & Verkoshansky, 1999; Stone et al., 2002; Young, 2006). Chapter 2 also considered how the similarity in movement pattern often referred to in the training specificity literature, might be better explained from a coordinative structure perspective, by understanding the similarity in the interaction between working joints that are functionally linked to satisfy the demands of a given task (Bernstein, 1967; Turvey, 1990).

It has been proposed (Newell, 1986) that humans adopt movement coordination patterns via a self-organisation process within the context of organismic, environmental and task related constraints imposed on the degrees of freedom of the system. These coordination patterns can be assessed through investigating the relative motion between joints of the same limb, providing a measure of intra-limb, inter-joint coordination (Hamill et al., 2012) and can improve our understanding of how movement is organised (Bernstein, 1967). Utilising intra-limb coordination patterns to compare the similarity between a training exercise and competitive motor task may provide a more detailed assessment of movement similarity and the potential effectiveness of an exercise to improve sports performance (Irwin & Kerwin, 2007a; Romanazzi et al., 2015; Wilson et al., 2009).

Chapter 3 provided biomechanical evidence to describe the motion of the ankle, knee and hip joints during the global phase of lower limb extension in the block start. The motions of these joints were presented independently and a task-specific pattern of joint motion was identified for each leg. Joint kinematic data revealed a flexion followed by extension pattern at both ankle joints, an extension pattern at both hip joints and the front knee joint, and an extension followed by flexion pattern at the rear knee joint. Within the front leg, a proximal-distal temporal pattern of ankle, knee and hip joint extension was identified that is commonly found in power demanding tasks (Jacobs et al., 1996). However, although the overall strategy was proximal-distal in nature, the exact coordination patterns between these joints
remains unknown. Furthermore, Chapter 3 identified the key joint kinetic determinants of starting block force production and overall performance. However, these variables were unable to account for all of the between athlete variance in block performance; therefore, investigating the interaction between joints may provide further explanation of how superior block performance is achieved.

As well as understanding intra-limb joint coordination whilst extending the lower limb during the block start, it is important to consider the inherently variable nature of human movement (Bernstein, 1967), which is an essential component in understanding the dynamics of movement (Hamill et al., 2000). Previous research has shown that in well-learned movements, low levels of outcome variability are associated with high levels of joint coordination variability (Bernstein, 1967). Variability in intra-limb joint coordination may thus promote a flexible and adaptable system that can explore coordination solutions to maintain task performance under varying constraints on action (Bernstein, 1967; Glazier & Davids, 2009; Hamill et al., 1999).

Previous research in the sporting context has identified that coordination variability can distinguish between task expertise, with more experienced performers often demonstrating greater magnitudes of coordination variability than their intermediate counterparts (Preatoni et al., 2010; Wilson et al., 2008), although contrary evidence has been shown (Cazzola, Pavei, & Preatoni, 2016). It is thus valuable to this research to investigate the influence of performance level on joint coordination variability, to not only advance mechanical understanding of the block start, but also how training exercises may exploit characteristics of successful performance.

The aim of this chapter was therefore to quantify intra-limb joint coordination and coordination variability during the execution of the block start and understand whether joint coordination and coordination variability is influenced by performance level. The following research questions will be addressed in Chapter 4:

**Research Question 5 – What are the patterns of intra-limb joint coordination and coordination variability when executing the block start?**
Research Question 6 – How are the intra-limb joint coordination patterns observed when executing the block start affected by the level of performer?

Research Question 7 – How is intra-limb joint coordination variability influenced by the level of performer?

Answering these research questions will contribute to achieving the main aim of the chapter. The purpose of the chapter was to provide novel understanding of movement dynamics in the block start, extending conventional biomechanical technique analysis to encompass the coordinated nature of human movement from a dynamical systems perspective. Performing this analysis will increase current knowledge of block start technique, and facilitate subsequent evaluations of training exercises based on the intra-limb joint coordinative features of the competitive motor task.

4.2 Methods

4.2.1 Participants
Seventeen male sprinters (mean ± SD: age, 23 ± 4 years; height, 1.79 ± 0.05 m; mass, 76.03 ± 5.40 kg) with 100 m personal best times ranging from 10.10-11.20 s (10.69 ± 0.33 s) gave written informed consent to participate in the study following institutional ethical approval. All athletes were free from injury at the time of data collection. The athletes sampled for this study were the same as in Chapter 3, and all athlete characteristics can be found in Table 3.1.

4.2.2 Data Collection
A cross sectional study design was implemented to understand joint coordination during the block start. Data were collected at the National Indoor Athletics Centre in Cardiff during normal block acceleration training sessions. After a coach prescribed warm up each athlete performed five (Athletes D and E) to six maximal 10 m sprints from blocks and three dimensional external kinetic and kinematic data were collected during the block phase.

External force data were collected using custom made instrumented starting blocks (Willwacher, Feldker, Zohren et al., 2013a) at 10000 Hz (post-processed to 1000
Hz) and were used to define the rear and front block phases. A more detailed description of the instrumented starting blocks can be found in Chapter 3. The rear and front block phases were defined between the instance of block start (earliest detection in which the first derivative of either the front or rear resultant force-time curve > 500 N.s⁻¹ and resultant force continued to rise to its maximum value) and the respective block end (rear / front block resultant force < 50 N).

Kinematic data were collected using a 15 camera (3x MXF20, 12x MX) three dimensional motion analysis system (Vicon, Oxford Metrics, UK, 250 Hz). Cameras were mounted on tripods to create a custom capture volume in which the block start could be measured. All cameras were calibrated to 3000 points to residual errors of < 0.3 mm using a 240 mm calibration wand. The origin of the capture volume was set with a right-handed orthogonal global coordinate system of X (medio-lateral), Y (anterior-posterior) and Z (superior). To collect marker trajectory data for the lower limbs, retro-reflective markers (14 mm) were attached to the participant’s skin bilaterally on the: iliac crest, posterior superior iliac spine, anterior superior iliac spine, lateral and medial femoral epicondyles, lateral and medial malleoli, first and fifth metatarsal heads, calcaneus, and head of the second toe (Fig. 3.3). Technical clusters comprising of four markers were attached towards the distal end of the thigh and shank segments (Manal et al., 2000).

4.2.3 Data Processing

Kinematic marker trajectories were labelled using Vicon Nexus (v1.8.5) and gap filled when necessary using both spline and pattern functions. After labelling of marker trajectories further data processing was performed using Visual 3D software (C-Motion Inc, Germantown, USA). A nine-segment model of the lower limb (pelvis and bilateral thigh, shank, foot and toe) was created with hip joint centres defined using regression equations (Bell et al., 1989). Knee and ankle joint centres were defined as the midpoint between the medial and lateral femoral epicondyles, and malleoli, respectively. The MTP joint centre was defined as the midpoint between the first and fifth metatarsal heads (Smith et al., 2014).

A static calibration was used to define each segment’s local coordinate system (SCS). For each SCS the x-axis pointed to the right, y-axis pointed forwards and z-axis pointed upwards. Raw marker coordinates were low-pass filtered (4th order Butterworth) with a cut-off frequency of 12 Hz, determined from residual analysis on
all tracking markers (Winter, 2009). Flexion-extension (x-axis) joint angles at the ankle, knee and hip for the front and rear leg were calculated as the transformation between proximal and distal SCS described by an X, Y, Z Cardan sequence of rotations (Selbie et al., 2014). Positive and negative angles represented extension/plantarflexion and flexion/dorsiflexion, respectively.

4.2.4 Quantification of Intra-Limb Joint Coordination & Variability: Modified Vector Coding of Relative Motion (Angle-Angle) Plots

Joint angle time-histories at the front and rear leg were normalised to 100% of the front and rear block phase, respectively, using a cubic spline. For each leg, angle-angle plots were then created for the hip-knee (H-K), hip-ankle (H-A) and knee-ankle (K-A) joint couples with the proximal and distal joint on the horizontal and vertical axis, respectively (Fig. 4.1).

4.2.4.1 Calculation of the Coupling Angle (CA)

Modified vector coding techniques were then employed to each angle-angle plot in order to quantify intra-limb joint coordination by calculating the coupling angle (CA) at each instance across the normalised phase duration (Fig. 4.1) (Sparrow et al., 1987; Chang et al., 2008; Needham et al., 2014). The coupling angle was calculated as the orientation of the vector between two adjacent points on the angle-angle plot relative to the right horizontal (Hamill et al., 2000).

The CA at each instant \( i \) during the normalised phase duration was computed based on the proximal \( (\theta_{P(i)}, \theta_{P(i+1)}) \) and distal joint angles \( (\theta_{D(i)}, \theta_{D(i+1)}) \) using the \( \text{atan2} \) function in Microsoft Excel:

\[
CA = \frac{180}{\pi} \times \left( \text{atan2} \left( \theta_{P(i+1)} - \theta_{P(i)}, \theta_{D(i+1)} - \theta_{D(i)} \right) \right)
\]  

[4.1]
Because the regular arctangent (atan) function only returns values in the first and fourth quadrants of a unit circle, the atan2 function was used to obtain values using all four quadrants of the unit circle and therefore yielding results between -180° and 180°. The quadrant to which CA belongs is based on the values of \( \theta_{P(i+1)} - \theta_{P(i)} \) and \( \theta_{D(i+1)} - \theta_{D(i)} \):

\[
\begin{align*}
\theta_{P(i+1)} - \theta_{P(i)} &> 0 \text{ and } \theta_{D(i+1)} - \theta_{D(i)} > 0, \quad \text{Quadrant 1, } 0^\circ \text{ to } 90^\circ \\
\theta_{P(i+1)} - \theta_{P(i)} &< 0 \text{ and } \theta_{D(i+1)} - \theta_{D(i)} > 0, \quad \text{Quadrant 2, } 90^\circ \text{ to } 180^\circ \\
\theta_{P(i+1)} - \theta_{P(i)} &< 0 \text{ and } \theta_{D(i+1)} - \theta_{D(i)} < 0, \quad \text{Quadrant 3, } -90^\circ \text{ to } -180^\circ \\
\theta_{P(i+1)} - \theta_{P(i)} &> 0 \text{ and } \theta_{D(i+1)} - \theta_{D(i)} < 0, \quad \text{Quadrant 4, } 0^\circ \text{ to } -90^\circ 
\end{align*}
\]

The coupling angle was subsequently corrected to present a value between 0° and 360° (Needham et al., 2014; Sparrow et al., 1987) by adding 360° if CA < 0.

Figure 4.1. Example angle-angle plot. The coupling angle (CA) is calculated by the vector orientation (dashed arrow) between two adjacent points relative to the right horizontal.
4.2.4.2 Average Calculations: Circular Statistics

Average CA (\( \overline{CA} \)) for each athlete over their five to six trials, and across all 17 athletes were calculated using circular statistics due to the directional nature of CA (Batschelet, 1981; Hamill et al., 2000). The average coupling angle were calculated based on the average horizontal (\( \overline{x_i} \)) and vertical (\( \overline{y_i} \)) components of CA at each instance of the normalised phase duration (\( i \)) (equations 4.2-4.4), and subsequently adjusted to again present a value between 0° and 360°:

\[
\overline{x_i} = \frac{1}{n} \sum_{i=1}^{n} \cos \left( \frac{\pi}{180} CA_i \right)
\]  [4.2]

\[
\overline{y_i} = \frac{1}{n} \sum_{i=1}^{n} \sin \left( \frac{\pi}{180} CA_i \right)
\]  [4.3]

\[
\overline{CA} = \frac{180}{\pi} \times (\text{atan2}((\overline{x_i}), (\overline{y_i})))
\]  [4.4]

4.2.4.3 Classification of Coupling Angle

Coupling angles were classified into one of four coordination patterns presented by Chang et al. (2008): in-phase, anti-phase, proximal and distal (Fig. 4.2). Each main coordination pattern was then subdivided based on the motion of the proximal and distal joints, providing eight distinct coordination patterns used to classify the calculated coupling angle and intra-limb joint coordination (Fig. 4.2). Each classification was assigned a colour, from which individual colour maps were created (see section 4.2.5).
4.2.4.4 Calculation of Coupling Angle Variability (CAV)

Using circular statistics (Batschelet, 1981; Needham et al., 2014), variability of CA at each instance across the normalised phase duration (CAV) could be computed from the resulting CA profile.

To calculate coupling angle variability (CAV), the length of the vector \( r_i \) between the \( \bar{x}_i \) and \( \bar{y}_i \) components of \( \overline{CA} \) were first calculated using equation 4.5.

\[
r_i = \sqrt{\bar{x}_i^2 + \bar{y}_i^2} \tag{4.5}
\]

Then, CAV was calculated according to equation 4.6.

\[
CAV_i = \frac{180}{\pi} \times \sqrt{2} \times (1 - r_i) \tag{4.6}
\]
4.2.5 Data Analysis
In order to understand the general patterns of front and rear leg joint coordination when executing the block start, ensemble average coupling angle profiles were calculated for all three joint couples (H-K, H-A, K-A), across all 17 participants, for each instance over the normalised phase duration (Equations 4.1-4.4). This was achieved by first calculating the mean CA for each participant using all trials, and then the group mean CA using each athlete’s mean data. Using the group average CA profile, the relative frequency (% of movement time) that CA lay within each of the eight coordination classifications was calculated for each joint couple.

To understand the effect of performance level on the observed coordination patterns, qualitative techniques were utilised to visualise the average CA profile for each athlete across the normalised phase duration. This was achieved by assigning a colour to each of the eight coordination patterns (Fig. 4.2), before plotting this colour profile across the normalised phase duration (Fig. 4.3).

![Figure 4.3. Example coupling angle (CA) profile and resultant colour map across the normalised time cycle.](image)
To understand the nature of joint coordination variability, CAV across the normalised phase duration (equations 4.5-4.6) were calculated for each athlete over all trials, and then averaged across all athletes to provide a group average measure of inter-trial coordination variability. Discrete values of joint coordination variability were also calculated for each athlete using individual CAV data, by averaging CAV across the entire phase duration (CA$_V$) and first 20% of the phase duration (CA$_V^{20}$).

To analyse the influence of performance level on joint coordination variability, quadratic regression analysis were utilised to identify the relationship between intra-athlete coupling angle variability and block performance (NAHP). Quadratic regressions were performed for each joint couple for two periods of the normalised phase durations: (1) across the entire phase duration (CA$_V$), and (2) across the first 20% (CA$_V^{20}$). Based on empirical evidence from previous research (Wilson et al., 2008) that has demonstrated a nonlinear relationship between expertise and joint coordination variability, quadratic regression were deemed most appropriate. The quadratic regression ($R^2$) value, which quantify how well the data are fitted to the regression line, were reported alongside a $P$ value to assess the statistical significance of the regression model. Statistical significance was accepted at an alpha level of 0.05.

### 4.3 Results

#### 4.3.1 Patterns of Intra-Limb Joint Coordination & Coordination Variability

Group average coupling angle (CA) and coupling angle variability (CAV) plots for the rear and front leg joint couples are presented in Figures 4.4-4.5. For each joint couple, the relative frequency of each CA classification is detailed in Figure 4.6.

In the rear leg, H-K joint coordination exhibited a predominantly in-phase pattern for the first 50% of rear block time. Following this, H-K joint coordination transitioned through proximal, anti-phase, and distal coordination patterns before the rear foot was no longer in contact with the block (Fig. 4.4). Joint coordination for the rear leg H-A couple was initially anti-phase whilst the ankle dorsiflexed and the hip extended. Then, as the ankle joint transitioned between dorsiflexion and plantarflexion the coordination pattern changed from proximal dominance to in-phase extension for 26% of rear block time. Finally, as hip extension slowed, a distal extension
coordination pattern existed for the final 22% of block time as the ankle joint continued to plantarflex (Fig. 4.4). A similar pattern of coordination existed for the K-A couple, with an initial period of anti-phase followed by proximal and in-phase extension coordination. However, the relative frequency of in-phase extension (8%) and distal extension (34%) coordination differed in comparison to the H-A couple (26% and 22%, respectively) (Fig. 4.6). Finally, a secondary period of anti-phase coordination at the end of rear block time was observed for the rear leg K-A joint couple (Fig. 4.4), which was opposite in nature to the beginning of the movement due to the presence of knee flexion but ankle plantarflexion.

Rear leg joint coordination variability profiles indicated that for all joint couples, the initiation of the block start was the period in which greatest between-trial variability was observed (Fig. 4.4). After this initial phase, joint coordination variability reduced, with secondary local maxima demonstrated for the H-K and K-A joint couples at approximately 80% and 50% of rear block time, respectively (Fig. 4.4).

In the front leg, only two coordination patterns were present for the H-K joint couple, an initial emergence of proximal extension coordination whilst the hip joint extended and the knee joint remained relatively still, followed by in-phase extension coordination as both joints extended prior to block exit (Fig. 4.5). The distribution of these two coordination patterns over block time was equal (Fig. 4.6). Front leg H-A coordination was similar to that of the rear leg (Fig. 4.4-4.5), beginning with anti-phase coordination before transitioning through proximal extension and in-phase extension coordination patterns. However, in the front leg a greater percentage of phase duration was spent in the proximal extension pattern (54% and 16% for the front and rear leg, respectively) (Fig. 4.6). Front leg K-A joint coordination was distributed across the same three patterns as for the H-A couple, with a final period of in-phase extension coordination (36%) proceeding anti-phase (20%) and proximal extension (34%) coordination patterns (Fig. 4.5-4.6).

As with the rear leg, front leg joint coordination variability exhibited largest magnitudes at the onset of movement (Fig. 4.5). For the H-K and H-A joint couples, coordination variability reduced and remained low (< 10°) for the remainder of the normalised phase duration. However, a secondary local maximum was found for the K-A joint couple at approximately 30-50% of block time, whilst coordination was transitioning between anti-phase and proximal extension patterns (Fig. 4.5).
Figure 4.4. Group average intra-limb joint coordination (CA) and coordination variability (CAV) data for the rear leg hip-knee (H-K), hip-ankle (H-A) and knee-ankle (K-A) joint couples during the rear block phase. Coordination patterns and colour code are detailed in Fig. 4.2 and 4.3.
Figure 4.5. Group average intra-limb joint coordination (CA) and coordination variability (CAV) data for the front leg hip-knee (H-K), hip-ankle (H-A) and knee-ankle (K-A) joint couples during the front block phase. Coordination patterns and colour code are detailed in Fig. 4.2 and 4.3.
Figure 4.6. Relative frequency of intra-limb joint coordination patterns during the rear (top row) and front (bottom row) block phases. Data are based on group average coupling angle (CA) data in Figures 4.4 and 4.5.
4.3.2 The Effect of Performance Level on Intra-Limb Joint Coordination & Variability

Figures 4.7 and 4.8 detail the individual athlete intra-limb joint coordination patterns for rear and front leg joint couples across the normalised phase duration. The colour coding of each coordination pattern (Fig. 4.3) provides qualitative visualisation of the differences in coordination patterns across the range of performance levels from the athletes utilised in the present study. Across all joint couples, the clearest trend for an effect of performance level on coordination pattern was observed for the front leg K-A couple (Fig. 4.8). This was demonstrated by athletes A-H showing more distal flexion (dark red) coordination across the first 40% of movement time, compared with athlete’s I-Q.

For all other joint couples, all athletes exhibited similarity in the main patterns of coordination (Fig. 4.7-4.8). In particular, at the front leg, all athletes settled into proximal extension and in-phase extension coordination patterns after the initial 30-50% of block time (Fig. 4.8). Whilst there appeared to be between-athlete differences in the duration of each main coordination pattern, there were no consistent differences between the higher and lower performing athletes (Fig. 4.7-4.8). In addition, these between-athlete differences were mainly observed during the onset of movement, after which there was more consistency in coordination patterns across all athletes (Fig. 4.7-4.8).
Figure 4.7. Individual rear leg intra-limb joint coordination colour maps during the rear block phase. Colour assignment is based on the coupling angle and the classifications presented in Figures 4.2 and 4.3.
Figure 4.8. Individual front leg intra-limb joint coordination colour maps during the front block phase. Colour assignment is based on the coupling angle and the classifications presented in Figures 4.2 and 4.3.
Plots of within-athlete joint coordination variability as a function of block performance are depicted in Figures 4.9 and 4.10. Coordination variability across the entire movement (CA\textsubscript{V}) and across the first 20% of movement (CA\textsubscript{V20}) are shown in 4.9 and 4.10, respectively. Quadratic regression analysis revealed that there was no consistent relationship between the magnitude of joint coordination variability and performance when considering all joint couples, with a mixture of positive and negative relationships observed (Fig. 4.9-4.10). The only significant quadratic relationship with block performance (R\textsuperscript{2} = 0.487, P < 0.05) was found for front leg H-A CA\textsubscript{V} (Fig. 4.9), in which the relationship was found to be negative.

For the first 20% of movement time, in which the greatest intra-athlete coordination variability was observed, the quadratic regressions with the highest R\textsuperscript{2} values were again found for CA\textsubscript{V20} at the H-A joint couple (front, R\textsuperscript{2} = 0.259, P > 0.05; rear, R\textsuperscript{2} = 0.195, P > 0.05) (Fig. 4.10). However, both were not found to be significant and were opposite in direction between the front (negative) and rear (positive) leg (Fig. 4.10), further highlighting inconsistency in the relationship between joint coordination variability and block performance.
Figure 4.9. Quadratic regression plots showing the relationship between block performance (NAHP) and average intra-limb joint coordination variability across the entire rear (top row) and front (bottom row) block phases (CAV). Quadratic regression R² and accompanying P-values are shown. *depicts a significant quadratic regression.
Figure 4.10. Quadratic regression plots showing the relationship between block performance (NAHP) and average intra-limb joint coordination variability across the first 20% of the rear (top row) and front (bottom row) block phases (CA_{V20}). Quadratic regression $R^2$ and accompanying $P$-values are shown. *depicts a significant quadratic regression.
4.4 Discussion
The aim of Chapter 4 was to quantify intra-limb joint coordination and coordination variability during the execution of the block start and understand whether joint coordination and variability was influenced by the level of performer. To contribute to an increased understanding of movement dynamics during the block start, vector coding techniques were applied to flexion-extension angle-angle plots in order to quantify the intra-limb joint coordination and variability of the three lower limb joint couples for each leg: hip-knee (H-K), hip-ankle (H-A), and knee-ankle (K-A).

Results highlighted that joint coordination variability was highest at the onset of block start execution, with proceeding stable patterns of proximal and in-phase extension coordination emerging for all front leg joint couples and the rear leg H-A couple. The main patterns of coordination demonstrated in the group analysis were shown to be mostly consistent with that observed on an individual level, although a trend towards superior performers eliciting a greater frequency of front leg K-A distal extension coordination was found. Many non-significant and inconsistent quadratic relationships between within-athlete joint coordination variability and block performance suggested that athletes of a higher level were not characterised by the magnitude of between-trial coordination variability.

4.4.1 Intra-limb Joint Coordination
To advance knowledge of the organisation of movement during the block start beyond single joint kinematics presented in Chapter 3, coupling angle data were calculated to provide a measure of coordination between functionally linked joints so that their interacting nature could be captured (Chang et al., 2008; Needham, Naemi, & Chockalingam, 2016).

One of the main differences in coordination patterns observed between the front and rear leg was the larger frequency of proximal extension coordination for the front leg H-A joint couple (54%) compared with the rear leg (16%), prior to in-phase extension coordination when both the hip and ankle joint were extending (Fig. 4.6). A proximal extension coordinative pattern for the H-A couple represents a scenario by which the hip joint is extending whilst the ankle stays relatively still, encompassing the period by which the ankle joint is reversing from dorsiflexion into plantarflexion (Chapter 3, Fig. 3.7-3.4). The shorter duration of proximal extension coordination pattern in the rear leg indicated a quicker transition between
dorsiflexion and plantarflexion, whereas in the front leg, the sustained period of proximal extension coordination (Fig. 4.5) highlighted a delay in ankle plantarflexion following its main phase of dorsiflexion. Chapter 3 previously highlighted that delaying the extension of the more distal joints in the front leg reflects the task constraints of the block phase requiring maximal forwards propulsion (Jacobs & van Ingen Schenau, 1992). However, different task constraints for the rear leg as a result of a shorter time in contact with the blocks (53 ± 2% of total block time, Chapter 3) may have influenced a quicker transition between ankle dorsiflexion and plantarflexion to provide the ankle joint with sufficient time to contribute to extensor energy generation and horizontal projection of the athlete (Debaere et al., 2015).

Other inter-limb differences were shown for the two joint couples encompassing the knee joint (H-K, K-A). Previous research (Bezodis et al., 2015; Mero et al., 2006) alongside that presented in Chapter 3 (Fig. 3.7-3.6) has highlighted the main source of asymmetry between legs in the block phase is apparent at the knee joint. The current study provided support to this notion, by explaining the exact effect of inter-limb differences in knee joint motion to emergent joint coordination patterns. Inter-limb differences were most prominent towards the end of each leg’s respective phase as the rear knee joint began to transition between extension and flexion (Fig. 4.4-4.5). For the H-K joint couple, anti-phase extension-flexion and distal flexion patterns manifested at the rear leg during the last 20% of movement compared with in-phase extension at the front leg. For the H-A joint couple inter-limb differences in coordination were apparent from 60% of movement time, with the rear leg showing more distal extension dominance prior to anti-phase flexion-extension, compared with dominant in-phase extension in the front leg (Fig. 4.4-4.5). To satisfy the requirement for movement pattern similarity between a training exercise and target skill so that sport specific adaptations can be facilitated (Young, 2006), the distinct inter-limb differences in coordinative patterns must be considered.

For all of the front leg joint couples, a large relative frequency was spent in proximal extension and in-phase extension coordinative states (Fig. 4.6). These two coordination patterns were solely reported for the H-K joint couple and after approximately 40% of block time for the H-A and K-A joint couples. This distinct pattern of coordination corroborates and supports that delayed extension of more distal joints occurs when executing the block start (Bezodis et al., 2015) in response to the task demand of maximising forwards propulsion (Jacobs & van Ingen Schenau, 1992).
Schenau, 1992). The coordination data presented in the current study allowed for deeper understanding of this sequencing, by detailing the exact interaction between the lower limb joints and highlighting the periods by which proximal extension, in-phase extension and distal extension coordination occurred.

The observed sequence of proximal extension to in-phase extension coordination coincided with low magnitudes of between-trial variability (Fig. 4.5). From a dynamical systems perspective, these coordination patterns can thus be indicative of task-specific coordinative structures (Kugler et al., 1980) or attractor states (Glazier, 2015) that emerge through self-organisation to the imposed constraints on action (Newell, 1986). Interestingly, all athletes were able to self-organise these particular coordination patterns regardless of different organismic (anthropometry, neuromuscular strength) and environmental (block settings) constraints (Fig. 4.8), providing further support to front leg proximal and in-phase extension as task specific coordinative structures (Kugler et al., 1980; Glazier, 2015). With respect to training, the effectiveness of an exercise to facilitate sport specific adaptation may be increased if these task-specific coordinative structures are promoted, so that altered organismic constraints can be effectively utilised within the task constraints of the block start (Bobbert & Van Soest, 1994; Irwin & Kerwin, 2007a; Moir et al., 2018; Romanazzi et al., 2015; Wilson et al., 2009).

Whilst understanding coordination patterns at the group level provided insight towards the general patterns of intra-limb coordination when executing the block start, consideration of the individual coordination profiles for each athlete (Fig. 4.7-4.8) permitted the investigation of whether coordination patterns could be linked to higher levels of performance. Results of the current study showed that of all joint couples, only the front leg K-A couple highlighted a performance related trend (Fig. 4.8). Specifically, the higher performing athletes showed a greater frequency of distal extension coordination during the first 40% of movement time (Fig. 4.8), suggesting that superior block performers were able to keep a stable front knee joint as the ankle underwent dorsiflexion. Greater stability at the front knee joint early in the block phase may have facilitated the transfer of large forces generated by the hip extensors (Chapter 3) to the point of force application, in order to maximise external force production at the onset of movement. The current study has extended previous block start research that has utilised single joint kinematics to investigate the techniques associated with superior performance (Bezodis et al., 2015;
Slawinski, Bonnefoy, Leveque et al., 2010a), by understanding movement through coordination patterns and providing novel insight into specific coordinative features of superior performance.

Although only the front leg K-A couple showed a link between performance level and coordination patterns, individual analysis highlighted that the onset of movement was the period during which the greatest inter-athlete differences were observed (Fig. 4.7-4.8). As it has been established that coordination variability is increased during changes to the state of the system (Heiderscheit, 2000), it could be theorised that the abrupt change in state when initiating movement resulted in the inter-athlete differences in coordination at movement onset. Furthermore, the different organismic constraints imposed on each athlete from their physical characteristics or set position may have influenced initial coordination patterns (Newell, 1986). For example, it has been found that coordination patterns were affected by starting angle of the knee joint during vertical jumps (Gheller et al., 2015). Therefore, inter-athlete differences in the set position may have influenced the initial interaction of the lower limb joints and emerging coordinative patterns. As all athletes settled into similar coordination patterns after 30-50% of block time, these inter-athlete differences at the onset of movement could be reflective of self-organisation towards adopting the task specific coordinative structures of proximal and in-phase extension (Newell, 1986).

4.4.2 Intra-limb Joint Coordination Variability

Variability in coordinative patterns during repeated trials of the same task has more recently been viewed as functional, allowing biological systems the flexibility to adapt to varying constraints by providing a range of solutions to complete a given motor task (Bernstein, 1967; Davids et al., 2003; Glazier, 2015; Hamill et al., 1999; Holt et al., 1995; James & Bates, 1997; Kelso, 1995; Van Emmerik et al., 2005). In the current study, coordination variability across all joint couples for the front and rear leg was found to be of greatest magnitude during the onset of movement (Fig. 4.4, 4.5). Similar results were observed by Wilson et al. (2016), who found that coordination variability was highest during the initiation of an explosive leg-press task, which, like the block start, adopted a stationary position prior to rapid extension of the lower limbs. The higher magnitude of variability at the onset of the leg press task was explained by the challenges of initiating movement of the leg press plate, demonstrating a need for additional flexibility / adaptability when physical demand
increases (Wilson et al., 2016). This notion applies to the abrupt change in state when the block phase commences, and can be linked to previous evidence that has shown that coordination variability can indicate an impending change in the state of a system (Haken et al., 1985; Heiderscheit, 2000).

For the front and rear K-A joint couple, coordination variability showed a second peak between 30-40% and 40-60% of movement time, respectively (Fig. 4.4, 4.5). Variability in coordination has been shown to increase when moving between coordination patterns, especially during the reversal in the direction of joint motion (Diedrich & Warren, 1995; Ghez & Sainburg, 1993; Haken et al., 1985; Heiderscheit, 2000; Needham et al., 2014). In the current study, the secondary peak in K-A joint coordination variability at the rear leg coincided with the termination of anti-phase coordination, as the ankle joint transitioned between dorsiflexion and plantarflexion whilst the knee joint extended (Fig. 4.4, 4.5).

At the front leg, the secondary local maxima in variability coincided with the transition between anti-phase, proximal phase, and in-phase coordination, this time as both the knee (onset of extension) and ankle joint (transition between dorsi and plantarflexion) were undergoing changes in motion. The more complex interaction between the knee and ankle joint in the front leg (i.e. both joints undergoing changes in motion at the same time) may explain the larger magnitude of variability in joint coordination observed in the front leg (Fig. 4.5) compared with the rear leg (Fig. 4.4). A second increase in joint coordination variability was also observed for the rear leg H-K couple towards the end of rear block time (Fig. 4.4) as the knee joint reversed from extension to flexion, again supporting that increases in variability can be indicative of impending changes in movement pattern (Heiderscheit, 2000).

Outside of the local maxima, joint coordination variability was small, suggesting that stable coordination patterns were present when executing the block start. These stable periods were especially apparent in the front leg for all joint couples when in-phase coordination emerged when both the proximal and distal joints were extending (Fig. 4.5). Low coordination variability during these periods of in-phase coordination may highlight the emergence of functionally stable attractor states or coordinative structures within the motor task (Kugler et al., 1980; Glazier et al., 2005). Therefore, the fluctuating nature of coordination variability across the front and rear block phases demonstrate the emergence of moving between stable
attractor states, characterised by higher variability around these transition points (Haken et al., 1985; Glazier, Wheat, Pease, & Bartlett, 2005).

The quantification of inter-trial coordination variability has detailed valuable information pertaining to the dynamics of movement and the stability (or instability) of coordination patterns that emerge when executing the block start. Based on previous evidence that has shown that movement variability can be influenced by task expertise (Robins, Davids, Bartlett, & Wheat, 2008; Wilson et al., 2008), the next phase of analysis was to explore whether coordination variability was influenced by the level of block performer. As the relationship between task expertise and movement variability has been shown to be of quadratic nature (Robins et al., 2008; Wilson et al., 2008), it was justified for the current study to utilise quadratic regression analysis to assess whether any relationships existed between coordination variability and block performance. Relationships were established using the average coordination variability across the entire phase ($CA_V$) and across the first 20% of movement ($CA_{V20}$), for both the front and rear leg.

Results showed that only one significant quadratic relationship ($R^2 = 0.488, P < 0.05$) was reported between coordination variability and performance, which was for $CA_V$ of the front leg H-A joint couple (Fig. 4.9). Although this relationship was negative, indicating features of an inverted U relationship, fitting a linear regression to this data also revealed a significant relationship and similar $R^2$ ($R^2 = 0.445, P < 0.05$). Therefore, the features of this relationship were linear in nature and explained a reduction in variability as performance level increased. Whilst this finding supports contention that successful task performance may require a smaller, functional range of variability (Glazier & Davids, 2009; Robins et al., 2008), there is not enough evidence in the current study to make any certain conclusions. Many of the quadratic relationships possessed $R^2$ values less than 0.2, and were a mixture of positive (U-shaped) and negative (inverted U-shaped) (Fig. 4.9-4.10).

Ultimately, there did not appear to be any consistent or significant non-linear relationships between coordination variability and block performance. This may be explained by rather homogenous sample of sprinters that, although differed in performance outcome (NAHP), could all be considered ‘experts’ in sprinting, given that all 100 m PB times were within 85-95% of the current world record. As a result, the current sample of athletes may have acquired relatively consistent coordination
patterns, and were able to exploit their inherent motor system variability in a functional manor, in order to adapt to particular organismic and environmental constraints between trials (Bartlett et al., 2007; Davids et al., 2003; Glazier & Davids, 2009; Hamill, 1999; Newell, 1986).

4.5 Conclusion
The introduction to this chapter identified three research questions that can be addressed following the current analysis:

**Research Question 5** – *What are the patterns of intra-limb joint coordination and coordination variability when executing the block start?*

To answer this question, intra-limb, inter-joint coordination was quantified by applying vector coding methods to angle-angle plots of the hip-knee (H-K), hip-ankle (H-A) and knee-ankle (K-A) joint couples, so that the resulting coupling angle and coupling angle variability could be profiled across the rear and front leg phases during the block start. Coupling angle data were classified into eight coordination patterns (Chang et al., 2008) to quantify the coordinative patterns demonstrated in the block start.

Differences in intra-limb joint coordination between the front and rear leg were most apparent for the H-K and K-A joint couples because of the asymmetrical action of the front and rear knee joint (Fig. 4.4-4.5). For H-A joint coordination, a key difference between the front and rear leg was identified to be a faster transition between anti-phase (extension-flexion) and in-phase extension patterns at the rear leg (Fig. 4.4, 4.5). Coordination patterns for all joint couples across both legs were most variable at the beginning of movement. This may reflect the search for stable coordinative patterns following the abrupt change in physical demand at the start of the task (Wilson et al., 2016), or differences in set position (organismic constraints) affecting the starting joint angles (Gheller et al., 2015).

In the front leg, periods of low inter-trial variability were observed when proximal and in-phase extension coordination patterns emerged. Therefore, especially with respect to the front leg, the presence of proximal dominated joint extension followed by in-phase extension of proximal and distal joints can be considered task specific
coordinative structures (Glazier, 2015; Kugler et al., 1980; Newell, 1986). These features of intra-limb coordination should therefore be targeted with respect to training exercises to satisfy the requirement of movement specificity (Siff & Verkoshansky, 1999), which is deemed essential for the positive transfer of altered organismic constraints (neuromuscular potential) to increased sports performance (Moir et al., 2018; Young, 2006).

**Research Question 6 – How are the intra-limb joint coordination patterns observed when executing the block start affected by the level of performer?**

Following the quantification of intra-limb joint coordination and variability, it was of interest to investigate whether athletes who achieved a higher level of block performance were able to present unique features of coordination that emerged during the execution of the block start. Colour maps were subsequently produced so that coordination profiles for all 17 sprinters could be qualitatively analysed. Of all joint couples, only front leg K-A coordination highlighted a performance related trend, with superior block performers showing a greater presence of distal extension coordination during the first 40% of movement (Fig. 4.8). The mechanical influence of this finding was theorised to reflect a strategy adopted by superior block performers to maintain a stable knee joint and allow the large forces generated by the hip joint transfer towards the ankle where they can be applied to the blocks.

Whilst no other consistent trends between coordination patterns and block performance were found, results highlighted that all athletes were able to self-organise similar patterns of coordination, after the onset of movement in which greatest inter-athlete variability was shown. Therefore, all athletes were able to manage their unique organismic constraints to adopt task specific coordinative structures relevant to block start execution.

**Research Question 7 – How is intra-limb joint coordination variability influenced by the level of performer?**

Quadratic regression techniques were employed to investigate the relationship between variability and block performance to understand whether coordination variability was influenced by the level of performer. Quadratic regressions were performed using variability data reflecting the entire (CAV) and the first 20% (CAV20) of the rear and front block phases, which encompassed the highest magnitude of
joint coordination variability. One significant relationship was observed for the front leg hip-ankle joint couple ($R^2 = 0.487$, $P < 0.05$) which showed a reduction in coordination variability as block performance increased. However, all other regression models were not significant and were inconsistent in direction (positive or negative), thus insufficient evidence was found to conclude a relationship between coordination variability and block performance.

Because the sample of athletes in the present study was relatively homogenous in their overall sprint ability (85-95% of 100 m word record time), the range of task expertise was unlikely large enough to detect a relationship between variability and block performance. All athletes were shown to possess a degree of between-trial coordination variability (Fig. 4.9-4.10) and likely represented a functional bandwidth of variability that permitted the exploitation of inherent motor system variability to adapt to between-trail constraints on task performance (Newell, 1986).

4.6 Chapter Summary
This study has investigated the dynamical nature of movement during the block start through the quantification of intra-limb joint coordination and coordination variability in 17 male sprinters. The presence of consistent and low variability proximal and in-phase extension coordination patterns at the front leg were observed (Fig. 4.5) and could be viewed as task specific coordinative structures associated with block start execution. These proximal extension and in-phase coordination patterns should thus emerge from a training exercise in order to satisfy the principle of specificity, to facilitate the positive transfer of biological adaptation (altered organismic constraints) to increased sports performance (Siff & Verkoshansky, 1999).

The identification of distal extension coordination being a feature of superior block performance (Fig. 4.8) added mechanistic understanding of the strategies adopted by more successful sprinters that appeared to be linked to the importance of initial stability of the front knee joint. The current study thus provided novel information to the movement patterns associated with superior block performance, moving beyond single joint kinematics (Bezodis et al., 2015, Slawinski, Bonnefoy, Leveque et al., 2010).
Joint coordination variability was found to be of greatest magnitude at the onset of movement and during reversal of ankle and knee joint motion (Fig. 4.4-4.5), supporting that variability increases during abrupt changes in state (Wilson et al., 2016) and when transitioning between coordination patterns (Heiderscheit, 2000). However, no clear patterns to suggest that the magnitude of coordination variability was influenced by the level of performer (Fig. 4.9-4.10) and could be reflective of the homogenous sample of task expertise regardless of differences in performance outcome. Instead, results suggested that all athletes promoted the inherent variability in human movement (Bernstein, 1967), allowing task specific coordinative structures to be maintained in response to subtle changes to constraints between trials (Bartlett, 2007; Newell, 1986). To satisfy the need for movement specificity within training exercises (Siff & Verkoshansky, 1999), an exercise should thus replicate the nature of coordination variability exhibited in the block start (Irwin & Kerwin, 2007a), promoting an adaptable system that can settle on task specific coordinative structures (proximal and in-phase extension) under imposed constraints on action (Newell, 1986).

The findings of the current study have pertinent implications for coaching practice, helping to develop the mind-set that coaches use to understand sports performance (Irwin et al., 2005). Influencing this mind-set and the way coaches perceive skills, can subsequently influence the training exercises that are selected to develop techniques that can serve to enhance performance of a sports skill (Irwin et al., 2005; Bolger et al., 2016).

**Research Phase 1 Summary**

In the introduction to this research (Chapter 1), a two-phase approach was established that would contribute to achieving the overall aim of the research: To advance understanding of the principles of overload and specificity within exercise selection. Through a review of literature (Chapter 2), it was established that possessing a biomechanical understanding of the competitive skill is fundamental for coaches’ selection of training exercises (Irwin et al., 2005; Moir et al., 2018), and to ensure that training is most relevant to the demands of the sport (Burnie et al., 2017; Siff & Verkoshansky, 1999; Winkelman, 2009). The first phase of this research, **Technique Analysis: Biomechanics**, has conducted a series of investigations to understand the biomechanics of block start technique.
In Chapter 3, conventional biomechanical analyses were conducted to understand
the external kinetic, joint kinematic and joint kinetic characteristics of block start
 technique. Novel insight into the musculoskeletal demand of executing the block
start was provided, alongside those joint kinetic techniques associated with superior
performance. In Chapter 4, block start technique was investigated from a dynamical
systems perspective by quantifying intra-limb joint coordination and variability.
Novel understanding of emergent coordination patterns and associated variability
furthered current knowledge of movement organisation in the block start (Bezodis
et al., 2015; Slawinski, Bonnefoy, Ontanon et al., 2010), and in combination with
conventional biomechanical analyses in Chapter 3, contributed to a holistic account
of block start technique.

The next phase of the current research will utilise the established biomechanical
understanding of the block start, to examine the training principles of overload and
specificity in order to facilitate informed and objective decisions within exercise
selection (Training Principles: Biomechanics Interface). Through consideration
of the principles of training (Dick, 2002; Matveyev, 1981; Siff & Verkoshansky, 1999;
Stone et al., 2002) from a constraints based framework (Newell, 1986), two themes
emerged through the preceding chapters of this research that can help understand
the potential of an exercise to enhance sports performance. Firstly, understanding
joint-level musculoskeletal demand through single joint kinematics and kinetics
can inform the magnitude and nature of imposed stress on the system that can lead
to musculoskeletal adaptation (Selye, 1951). Secondly, understanding the self-
organisation of intra-limb joint coordination and variability provides knowledge of the
movement dynamics associated with executing a competitive task, influencing the
task specific utilisation of musculoskeletal adaptation to enhance sports
performance. These two themes established a theoretical framework for comparing
a training exercise with a competitive sports skill and formed Phase 2 of the current
research.
CHAPTER 5. A BIOMECHANICAL EVALUATION OF TRAINING EXERCISES FOR ENHANCING BLOCK START PERFORMANCE

5.1 Introduction
Performance in the starting blocks is of key importance to overall performance in the short sprint events (Willwacher et al., 2016), and there is great desire to improve block performance by utilising the most effective training exercises. Sprint coaches utilise a range of exercises (e.g. heavy resistance, ballistic, plyometric) in order to develop underpinning neuromuscular qualities and task specific strength (Bolger et al., 2016). The selection of training exercises is typically based on the principle of specificity, viewed as maximising similarity with a competitive motor task (Burnie et al., 2017; Moir et al., 2018; Wild et al., 2011). Within the context of sprinting, this view has led to exercises being traditionally placed on a spectrum from general (not specific) to specific, often based on similarity of gross movement pattern and velocity (Rumpf et al., 2016; Wild et al., 2011; Young et al., 2001).

However, this unidimensional (similarity) approach ignores the fundamentals of specificity, which requires neuromuscular adaptation and thus an overload stimulus (Matveyev, 1981). Assessing the efficacy of strength training based on replication alone, devalues its potential role to promote favourable neuromuscular-skeletal adaptations that can allow the athlete to overcome their biomechanical limitations to performance (Moir et al., 2018). It is therefore essential that overload and specificity be concurrently addressed when evaluating the potential effectiveness of a training exercise.

Biomechanical needs analyses are encouraged in the applied setting to ensure training is most relevant to the sport (Young et al., 2001; Wild et al., 2011; Winkelman, 2009). To develop a detailed understanding of block start biomechanics, two themes were examined in the preceding Chapters. Firstly, in Chapter 3, single joint kinematics and kinetics provided information towards the nature of musculoskeletal demand when executing the block start. Secondly, Chapter 4 utilised intra-limb, inter-joint coordination and variability to understand the movement dynamics of executing the block start. The current Chapter combines these themes in a biomechanical comparison between the block start (competitive
motor task) and training exercises, providing a unified analysis of overload and specificity.

In Chapter 3 (Brazil et al., 2017; 2018), novel information of the joint kinetic variables associated with external force production (average F_Y) and overall block performance (NAHP) were established. In accordance with the principle of overload (Matveyev, 1981; Dick, 2002; Siff & Verkoshansky, 1999), a strength training exercise aimed at improving block start performance should elicit a greater magnitude of these key joint kinetic determinants, so that sport specific physiological adaptation can occur. However, training theory acknowledges that joint kinetic overload should occur at a similar joint angle, so the nature of musculoskeletal stress is specific to the joint positions experienced in the competitive task (Morrissey et al., 1995; Siff & Verkoshansky, 1999). By utilising single joint kinematics and kinetics, the functional nature of musculoskeletal overload can be addressed to further inform exercise selection.

Coach perception (Bolger et al., 2016; Burnie et al., 2017) and empirical evidence (McBride et al., 2002; Wilson et al., 1996) has supported that similarity in movement patterns can facilitate sport specific adaptations to strength training and the transfer of training to improved sports performance (Young, 2006). From a dynamical systems perspective, movement emerges through a process of self-organisation based on the intentions of the performer and the constraints imposed on the system (Kugler et al., 1980; 1982; Newell, 1986). In this context, movement is often analysed through the coordination of functionally linked segments or joints (Hamill et al., 2000). As such, Chapter 4 quantified the intra-limb, inter-joint coordination patterns that emerged when executing the block start. To satisfy the requirement for movement pattern similarity, these coordination patterns should emerge from a training exercise in order to maximise the transfer of training (Irwin & Kerwin, 2007a; Romanazzi et al., 2015, Wilson et al., 2009).

As joint coordination is self-organising in response to organismic, environmental and task constraints (Newell, 1986), inherent inter- and intra-individual variability exists. Within a constraints led approach, promoting variability present in a competitive motor task is important to ensuring flexible and adaptable systems (Hamill et al., 2012; Kelso, 1995; van Emmerik et al., 2005). The framework of constraints (Newell, 1986), and redundancy in the human motor system to achieve tasks (Bernstein,
provides theoretical explanation for the individual strategies commonly observed in biomechanics literature (Bradshaw et al., 2007; Dufek & Bates, 1990; Exell, Irwin, Gittoes, & Kerwin, 2016), and individual responses to training (Astorino & Schubert, 2014; Bouchard & Rakinen, 2001; Hubal et al., 2005; Karavita et al., 2011; Newton et al., 2002). Individual biomechanical strategies may thus influence overload and/or specificity of a training exercise, and should be considered in an exercise selection process.

The acquisition of a mind-set for a competitive skill has been shown to influence exercise selection in elite coaches (Irwin et al., 2005). By undertaking biomechanical analyses of both the competitive task and training exercises, this mind-set can be influenced to facilitate objective exercise selection based on the biomechanical determinants of performance. The aim of this chapter was therefore to evaluate characteristics of musculoskeletal demand and movement dynamics for a range of training exercises in reference to the block start. The following research questions will be addressed in Chapter 5:

**Research Question 8** – How do lower limb joint kinematics and kinetics compare between the block start and traditionally viewed general and more specific training exercises?

**Research Question 9** – How does inter-joint coordination and coordination variability compare between the block start and traditionally viewed general and more specific training exercises?

The purpose of the chapter was to inform objectivity within exercise selection and contribute to theoretical understanding of the principles of training. Performing an in depth biomechanical analysis of musculoskeletal demand and movement dynamics in a holistic nature will facilitate a platform for this approach within biomechanics research and applied strength and conditioning practices.
5.2 Methods

5.2.1 Participants
Six male sprinters gave written informed consent to participate in the study following institutional ethical approval. All athletes were free from injury at the time of data collection. The six athletes for this study were obtained from the same sample population in Chapters 3 and 4. Updated athlete characteristics are shown in Table 5.1. As the data for this study was obtained over two sessions (S1 and S2), body mass for each is shown.

Table 5.1. Athlete characteristics

<table>
<thead>
<tr>
<th>ID</th>
<th>Age (yrs)</th>
<th>Height (m)</th>
<th>Leg Length (m)</th>
<th>Mass (S1) (kg)</th>
<th>Mass (S2) (kg)</th>
<th>100 m PB (s)</th>
<th>60 m PB (s)</th>
<th>NAHP Rank (NAHP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>21</td>
<td>1.79</td>
<td>0.907</td>
<td>73.46</td>
<td>76.33</td>
<td>10.92</td>
<td>7.04</td>
<td>0.528</td>
</tr>
<tr>
<td>K</td>
<td>20</td>
<td>1.83</td>
<td>0.901</td>
<td>71.35</td>
<td>72.60</td>
<td>10.72</td>
<td>7.08</td>
<td>0.493</td>
</tr>
<tr>
<td>L</td>
<td>20</td>
<td>1.72</td>
<td>0.834</td>
<td>75.83</td>
<td>75.24</td>
<td>10.95</td>
<td>6.99</td>
<td>0.484</td>
</tr>
<tr>
<td>M</td>
<td>20</td>
<td>1.88</td>
<td>0.928</td>
<td>81.27</td>
<td>84.20</td>
<td>11.00</td>
<td>6.94</td>
<td>0.481</td>
</tr>
<tr>
<td>N</td>
<td>26</td>
<td>1.83</td>
<td>0.908</td>
<td>78.56</td>
<td>79.98</td>
<td>10.68</td>
<td>6.93</td>
<td>0.472</td>
</tr>
<tr>
<td>Q</td>
<td>28</td>
<td>1.89</td>
<td>0.905</td>
<td>90.64</td>
<td>92.23</td>
<td>10.64</td>
<td>6.81</td>
<td>0.452</td>
</tr>
<tr>
<td>Mean</td>
<td>23</td>
<td>1.82</td>
<td>0.897</td>
<td>78.52</td>
<td>80.10</td>
<td>10.82</td>
<td>6.97</td>
<td>0.485</td>
</tr>
<tr>
<td>SD</td>
<td>4</td>
<td>0.06</td>
<td>0.03</td>
<td>6.91</td>
<td>7.18</td>
<td>0.16</td>
<td>0.10</td>
<td>0.025</td>
</tr>
</tbody>
</table>

5.2.2 Data Collection
A cross sectional study design was implemented in order to quantify the biomechanics of seven training exercises that could be compared to biomechanical data obtained for the block start in Chapters 3 and 4. Data were collected over two separate sessions (S1 and S2), separated by eight to twelve weeks, in order to align with the phase of training. All data were collected in the National Indoor Athletics Centre in Cardiff in conjunction with normal strength and conditioning training sessions. The selected exercises are described in detail in Table 5.2. Although direct rationale for each exercise is provided in Table 5.2, the seven exercises were selected to encompass both traditionally viewed general (JS<sub>0</sub>, JS<sub>60</sub>, BS<sub>90</sub>) and more specific (HJ<sub>BL</sub>, HJ<sub>SP</sub>, MBD<sub>BL</sub>, MBD<sub>SP</sub>) exercises (Crick, 2009; Rumpf et al., 2016; Wild et al., 2011). All coaches were involved in the selection of each exercise and athletes were familiar with each exercise prior to data collection.
Table 5.2. Exercise descriptions. The level of ‘specificity’ in accordance with contemporary practice (Crick, 2009), reduces in descending order.

<table>
<thead>
<tr>
<th>Exercise Name</th>
<th>Exercise Description</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Split Stance Medicine Ball Dive (MBD&lt;sub&gt;SP&lt;/sub&gt;)</td>
<td>Same as MBD&lt;sub&gt;BL&lt;/sub&gt;, but adopting the split stance position, matching the front and rear foot setup in the block start.</td>
<td>The split stance foot positions were chosen in order to understand the effect of manipulating task demands (stance) to alter the external appearance of the exercise to closer replicate the block start (in comparison with HJ&lt;sub&gt;BL&lt;/sub&gt; and MBD&lt;sub&gt;BL&lt;/sub&gt;).</td>
</tr>
<tr>
<td>Split Stance Horizontal Jump (HJ&lt;sub&gt;SP&lt;/sub&gt;)</td>
<td>Same as HJ&lt;sub&gt;BL&lt;/sub&gt;, but adopting a split stance position (one foot in front of the other to emulate the nature of the block start). Each athlete positioned their front and rear leg to match that of their block start setup.</td>
<td></td>
</tr>
<tr>
<td>Bilateral Medicine Ball Dive (MBD&lt;sub&gt;BL&lt;/sub&gt;)</td>
<td>The athlete adopts a crouched position with a 5 kg medicine ball close to the chest. Then, the athlete explosively dives forwards whilst throwing the medicine ball in the horizontal direction. For safety, the athlete dives onto a crashmat following the release of the medicine ball.</td>
<td>Ballistic exercises that involve jumping are commonly used by sprint coaches (Bolger et al., 2016), and those executed in the horizontal direction are typically better related to sprint acceleration performance (Maulder &amp; Cronin, 2006). Horizontal jumps are recommended as specific preparatory exercises to develop sprint acceleration (Wild et al., 2011). Furthermore, the horizontal jump and medicine ball dive were being used by all athletes in the current study and it was of interest to the coaches to understand the role of these exercises.</td>
</tr>
<tr>
<td>Bilateral Horizontal Jump (HJ&lt;sub&gt;BL&lt;/sub&gt;)</td>
<td>From a normal standing position, the athlete performs a horizontal jump with countermovement, with the objective of projecting as far as possible in the horizontal direction.</td>
<td></td>
</tr>
<tr>
<td>Concentric only Jump Squat with no external load (JS&lt;sub&gt;0&lt;/sub&gt;)</td>
<td>With a barbell placed across the shoulders the athlete descends until the bar settles on safety blocks, corresponding to approximately 90° knee flexion. From this stationary starting position, the athlete explosively jumps into the air to maximise jump height.</td>
<td>The jump squat is considered a gold standard exercise to develop lower limb extensor power and is commonly used amongst sprint coaches (Bolger et al., 2016). The stationary starting position increases relevance to the mechanical demands of the block start. Including two external loads allows for the exploration of differences towards opposite ends of the force-velocity curve within the same movement. Previous research has suggested the use of multiple external loads for maximum power development (Cormie et al., 2011; Jandacka et al., 2014).</td>
</tr>
<tr>
<td>Concentric only Jump Squat with 60% 1RM external load (JS&lt;sub&gt;60&lt;/sub&gt;)</td>
<td>With a barbell placed across the shoulders loaded to 60% 1RM the athlete descends until the bar settles on safety blocks, corresponding to approximately 90° knee flexion. From this stationary starting position, the athlete explosively jumps into the air to maximise jump height.</td>
<td></td>
</tr>
<tr>
<td>Concentric only Back Squat with 90% 1RM external load (BS&lt;sub&gt;90&lt;/sub&gt;)</td>
<td>With a barbell placed across the shoulders loaded to 90% 1RM the athlete descends until the bar settles on safety blocks, corresponding to approximately 90° knee flexion. From this stationary starting position, the athlete aims to stand with the intent of moving as fast as possible.</td>
<td>The back squat is considered a gold standard exercise to develop lower limb extensor strength and is commonly used amongst sprint coaches (Bolger et al., 2016). The stationary starting position increases relevance to the mechanical demands of the block start.</td>
</tr>
</tbody>
</table>
5.2.2.1 Experimental Procedures

Data collections were split across two sessions. The first session (S1) included ballistic, horizontally projected jump exercises (HJ\textsubscript{BL}, MBD\textsubscript{BL}, HJ\textsubscript{SP}, MBD\textsubscript{SP}), and the second (S2) included back squat and jump squat variations (JS\textsubscript{0}, JS\textsubscript{60}, BS\textsubscript{90}) (Table 5.2). At the beginning of each session, athletes completed their regular warm up for the particular type of exercise to be completed. The exercises in S1 were performed in a randomized order, whereas in S2 all participants performed BS\textsubscript{90} prior to a randomized order of JS\textsubscript{0} and JS\textsubscript{60}. The rationale for performing BS\textsubscript{90} first was so that the athletes could safely prepare for the greatest external load to be lifted.

In order to determine the external loads to be lifted in S2, prior testing was performed to estimate each athlete’s 1RM concentric only back squat. This also served to establish the height of the safety blocks to set the athlete into a position of approximately 90° knee flexion at the beginning of the lift. In this session, all athletes performed their typical warm up for back squats followed by three repetitions at 60% of estimated 1RM. Following this, the loads increased incrementally until the athlete self-determined the load in which they could not lift for more than three repetitions. Based on this three-repetition maximum (3RM), 1RM was estimated by 3RM / 0.93 (Beachle & Earle, 2008).

Consequently, the external loads during BS\textsubscript{90} and JS\textsubscript{60} were calculated as the percentage of this predicted 1RM rounded to the nearest 2.5 kg (due to the minimum increment of the weight plates). Mean ± SD loads were 102.5 ± 12.5 kg and 152.5 ± 17.5 kg, for JS\textsubscript{60} and BS\textsubscript{90}, respectively. For JS\textsubscript{0} a 5 kg barbell with 2.5 kg Olympic bumper plates each side were used as standard for all athletes, to ensure the same starting position as for the other concentric squat variations. During testing, two sets of three repetitions were performed with each load totalling six trials for each exercise.

5.2.2.2 Collection of Kinetic & Kinematic Data

Three dimensional (3D) kinematic and kinetic data were collected to compare biomechanical variables between each training exercise and the block start. Data collection procedures were kept as similar as possible to those detailed in Chapter 3 in order to protect consistency of methods.
Kinematic data were collected using a 15 camera 3D motion analysis system (Vantage, Vicon, Oxford Metrics, UK) sampling at 250 Hz. Cameras were mounted to a custom rig inside the Biomechanics laboratory at Cardiff Metropolitan University, in order to create a custom capture volume for the requirements of the current study. All cameras were calibrated to 3000 points to residual errors of < 0.3 mm using a 240 mm calibration wand. The origin of the capture volume was set with a right-handed orthogonal global coordinate system of X (medio-lateral), Y (anterior-posterior) and Z (superior). Marker trajectory data were obtained from 14 retro-reflective markers (14 mm) that were attached to the skin of each athlete using adhesive tape. Four rigid clusters comprising four markers were attached towards the distal end of the thigh and shank segments (Manal et al., 2000). Markers were placed at the same anatomical locations as per Figure 3.3, in order to replicate the lower limb model used to collect data from the block start in Chapter 3.

External ground reaction force data resulting from the force applied through the corresponding front and rear leg to the block start were collected independently from two Kistler force platforms (9287BA, Kistler, Switzerland) sampling at 1000 Hz. External force signals were internally amplified and collected simultaneously with the Kinematic data using Vicon Nexus (v2.2.3).

5.2.3 Data Processing
For all exercises, the global movement phase that provided a valid comparison with the block start (i.e. lower limb extension) was first defined. For the squat variations in S2, the start onset was defined using filtered external force data (4th order Butterworth at 60 Hz cut-off) as the earliest detection in which the first derivative of either the left or right resultant force-time curve ($F_R$) > 500 N.s⁻¹. Due to the ‘bottom up’ nature of the exercise, commencing from a stationary position, this represented the onset of force application in order to extend the lower limb, and was aligned with the onset threshold for the block start (Chapter 3). The end of the squat exercise was taken as the local minima in vertical force as the barbell approached maximal vertical displacement, and for the jump squat exercises, when vertical force (using raw, unfiltered signals) descended below 10 N.

For the exercises in S1, the onset of movement was defined as the onset of hip extension (angular velocity > 0). This decision was made because of the varying nature of the force-time data compared with the block start and squat variations,
and allowed consistency between those performed with and without a preceding countermovement. Selecting the onset of hip extension reflected the global onset of lower limb extension, and the end of the movement was again identified when raw vertical force was < 10 N. For exercises adopting a split stance (HJ\textsubscript{SP} and MBD\textsubscript{SP}), separate rear and front leg end thresholds were identified when the respective raw vertical force was < 10 N, establishing two (rear and front) sub-phases for these exercises.

Kinematic marker trajectories were first labelled in Vicon Nexus (v2.2.3) and gap filled when necessary using both spline and pattern functions. After marker labelling, all further processing was performed in Visual 3D (v6, C-Motion Inc, Germantown, USA) where a nine segment model of the lower limb (pelvis and bilateral thigh, shank, foot and toe) was created. This model possessed the same segmental properties as used in Chapter 3. In particular, hip joint centres were defined using regression equations (Bell et al., 1989), knee and ankle joint centres as the mid-point between the medial and lateral femoral epicondyles, and malleoli, respectively, and the MTP joint centre as the mid-point between the first and fifth metatarsal head (Smith et al., 2014).

Raw marker coordinates were low-pass filtered (4\textsuperscript{th} order Butterworth) with a cut-off frequency of 8 Hz, determined as the average cut-off frequency from a residual analysis and curve rotation on all tracking markers (Winter, 2009; Mullineaux, 2017). Joint angles were calculated as the transformation between two SCS described by an X, Y, Z Cardan sequence of rotations (Selbie et al., 2014), with positive and negative angles representing flexion/dorsiflexion and extension/plantarflexion, respectively. Extensor range of motion (ROM) was calculated as the difference between the minimum and maximum joint angle during each task.

To quantify joint kinetic data, Newton-Euler inverse dynamics procedures (Selbie et al., 2014) were used to calculate flexion-extension (x-axis) joint moments at the ankle (\textit{ANK}), knee (\textit{KNE}) and hip (\textit{HIP}), using Visual 3D (Chapter 3). Joint power was calculated as the product of joint moment and angular velocity and the main phases of positive extensor power were identified for each joint during each exercise. Peak and average extensor moment (M) and positive extensor power (P) were quantified at each joint and normalised as outlined in Chapter 3.
To quantify intra-limb joint coordination, joint angle time-histories for the ankle, knee and hip for each leg were first normalised to 100% of their respective phase, before creating angle-angle plots for the hip-knee (H-K), knee-ankle (K-A) and hip-ankle (H-A) joint couples. Vector coding techniques outlined in Chapter 4 were then utilised to calculate the coupling angle (CA) between adjacent points on the angle-angle plots relative to the right horizontal (Hamill et al., 2000). The CA at each instance during the normalised phase duration was computed using formula 4.1 and the within-athlete average CA across multiple trials was computed using circular statistical methods (Batschelet, 1981) (equations 4.3-4.5). The same equations were then utilised to calculate the group average CA using each within-athlete average CA data, in order to identify the global joint coordination patterns for each exercise. CA values were presented between 0° and 360° as outlined in section 4.2.4.1. Intra-limb joint coordination variability (the variability across multiple trials of the same exercise) for each athlete was calculated using equations 4.6 and 4.7, before group average values were computed across the entire movement ($CA_V$) and for the first 20% of movement ($CA_{V20}$) (see Chapter 4 for additional details).

5.2.4 Data Analysis

Both discrete and continuous analyses were adopted in order to understand the magnitude and nature of specificity and overload characteristics for each exercise in comparison with the block start. For non-circular data, group mean and between-athlete standard deviations were calculated using each athlete's mean data from all trials. To investigate the differences between each exercise and the block start, the same procedures were used as outlined in Chapter 3, by computing standardised effect sizes ($d$) and magnitude based inferences (MBI) were made using 90% confidence intervals and a threshold of 0.6 (moderate) for the smallest meaningful difference (Batterham & Hopkins, 2006). Effect size, confidence intervals and MBI data were calculated based on the formulas provided in the post-only crossover analysis spreadsheet by Hopkins (2006). The percentage likelihood of the true difference being at least moderately positive (>0.6) or negative (<-0.6) was used to make the following inferences: possibly (25-75%), likely (75-95%), very likely (95-99.5%), and almost certain (>99.5%). Any effect in which the percentage likelihood of a positive or negative effect was <25% was deemed not different.

The direction of the effect indicated whether the training exercise (positive) or block start (negative) was of greater magnitude. A meaningful difference was considered
when the likelihood of a moderate difference was at least ‘likely’. In addition to MBI, the magnitude of the effect size was also used to distinguish levels of difference, using the scale provided by Hopkins et al. (2009): moderate \(0.6 \leq d < 1.2\), large \(1.2 \leq d < 2.0\), very large \(2.0 \leq d < 4.0\), and extremely large \(d \geq 4.0\). The same scales were used for both positive and negative effect sizes. All discrete data were confirmed to be normally distributed (Shapiro-Wilk \(P > 0.05\)) prior to analysis.

To support the discrete data, data visualisation techniques were employed in order to investigate the local differences in biomechanical data across a time series (Manal & Stanhope, 2004). To achieve this, joint angle, moment and power data at the ankle, knee and hip were first normalised to 100% of the rear and front leg phases using a cubic spline in Visual 3D. Ensemble mean and standard deviation time histories were then produced to quantify the average and between-athlete variation in kinematic and kinetic patterns. To provide a scale of difference at each point across the normalised phase cycle, standardised effect size differences \(d\) were calculated at each instance, and its magnitude converted into a specific colour value of red (R), green (G) and blue (B) based on the scale outlined above (Table 5.3). The outcome was a colour spectrum that ranged through red (extremely large negative difference (block start > exercise)) through to green (no meaningful difference), to blue (extremely large positive difference (block start < exercise)).
Table 5.3. Contributions of red (R), green (G) and blue (B) to the colour assignments across the effect size scale (-4 to +4) for values of \( d \). The direction of \( d \) indicates whether the block start (negative) or training exercise (positive) was of greater magnitude.

<table>
<thead>
<tr>
<th>( d )</th>
<th>Interpretation</th>
<th>R</th>
<th>G</th>
<th>B</th>
<th>Colour</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d &lt; -4.0 )</td>
<td>Extremely large negative difference</td>
<td>255</td>
<td>0</td>
<td>0</td>
<td><img src="https://via.placeholder.com/150x150.png" alt="" /></td>
</tr>
<tr>
<td>(-2.0 \leq d &gt; -4.0 )</td>
<td>Very large negative difference</td>
<td>255</td>
<td>128</td>
<td>0</td>
<td><img src="https://via.placeholder.com/150x150.png" alt="" /></td>
</tr>
<tr>
<td>(-1.2 \leq d &gt; -2.0 )</td>
<td>Large negative difference</td>
<td>255</td>
<td>255</td>
<td>0</td>
<td><img src="https://via.placeholder.com/150x150.png" alt="" /></td>
</tr>
<tr>
<td>(-0.6 \leq d &gt; -1.2 )</td>
<td>Moderate negative difference</td>
<td>128</td>
<td>255</td>
<td>0</td>
<td><img src="https://via.placeholder.com/150x150.png" alt="" /></td>
</tr>
<tr>
<td>(-0.6 &lt; d &lt; 0.6 )</td>
<td>Not different</td>
<td>0</td>
<td>255</td>
<td>0</td>
<td><img src="https://via.placeholder.com/150x150.png" alt="" /></td>
</tr>
<tr>
<td>( 0.6 \leq d &lt; 1.2 )</td>
<td>Moderate positive difference</td>
<td>0</td>
<td>255</td>
<td>128</td>
<td><img src="https://via.placeholder.com/150x150.png" alt="" /></td>
</tr>
<tr>
<td>( 1.2 \leq d &lt; 2.0 )</td>
<td>Large positive difference</td>
<td>0</td>
<td>255</td>
<td>255</td>
<td><img src="https://via.placeholder.com/150x150.png" alt="" /></td>
</tr>
<tr>
<td>( 2.0 \leq d &lt; 4.0 )</td>
<td>Very Large positive difference</td>
<td>0</td>
<td>128</td>
<td>255</td>
<td><img src="https://via.placeholder.com/150x150.png" alt="" /></td>
</tr>
<tr>
<td>( d &gt; 4.0 )</td>
<td>Extremely large positive difference</td>
<td>0</td>
<td>0</td>
<td>255</td>
<td><img src="https://via.placeholder.com/150x150.png" alt="" /></td>
</tr>
</tbody>
</table>

Due to the circular nature of joint coordination (CA) data, the same effect size method could not be employed. As coordination patterns are often ‘binned’ into distinct patterns (Chang et al., 2008, Chapter 4), a modified colour spectrum was used to visualise differences in joint coordination patterns. The colour assigned at each instance of the normalised time cycle was based on the difference in coordination pattern (or bin), which ranged from a minimum of ‘0’ (same coordination pattern, green colour), to a maximum of ‘4’ (opposite side of the classification circle, red colour) (Fig. 5.1).

The contributions of RGB to the colour assignment were consistent with that for negative effect sizes in Table 5.3. To provide a discrete value that could be used to quantify the overall similarity in joint coordination, a coupling angle difference (\( CA_{DIF} \)) was calculated. This was achieved by summing the difference scores (Fig. 5.1) across the normalised time cycle and expressing this value as a percentage of the maximum possible value. Therefore, \( CA_{DIF} \) represented the global difference in joint coordination between each exercise and the block start, in which a lower magnitude of \( CA_{DIF} \) indicated greater similarity with the coordination patterns exhibited in the block start. \( CA_{DIF} \) was also computed on a within-athlete basis using each athlete’s average CA profile for the block start and each exercise.
Figure 5.1. Representation of all possible difference scores and colour assignment based on the coordination classification of two tasks at one instance of the normalised time cycle. The black filled circle represents the competitive motor task (block start) and black outlined circles represent all possible differences for a training exercise at a given instance.

5.3 Results
To present the results, the two themes of analysis, musculoskeletal demand (single joint kinematics and kinetics) and movement dynamics (intra-limb joint coordination and variability) will be presented in sequence.

5.3.1 Musculoskeletal Demand (single joint kinematics & kinetics)
Discrete joint kinetic data and MBI inferences are presented in Table 5.4. Figures 5.2-5.10 detail the continuous nature of joint angle, moment and power data.
Table 5.4. Group mean (±) SD joint kinetic data at the rear and front leg. Standardised effect size ($d$) and 90% confidence intervals (CI) between the block start and each exercise are shown. Inferences are based on the likelihood of the true value of $d$ being moderate (0.6 or -0.6).

*Note. Acronym identifies MBI: ND = not different, P = possible, L = likely, VL = very likely, AC = almost certain.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Block Start</th>
<th>JS</th>
<th>JSSE</th>
<th>BSSE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>SD</td>
<td>mean</td>
<td>SD</td>
</tr>
<tr>
<td>Peak $M_{\text{RNX}}$</td>
<td>0.202 ± 0.018</td>
<td>0.204 ± 0.014</td>
<td>0.11</td>
<td>-0.69</td>
</tr>
<tr>
<td>Peak $M_{\text{RNE}}$</td>
<td>0.080 ± 0.042</td>
<td>0.214 ± 0.020</td>
<td>3.42</td>
<td>2.67</td>
</tr>
<tr>
<td>Peak $M_{\text{RNP}}$</td>
<td>0.290 ± 0.043</td>
<td>0.220 ± 0.026</td>
<td>-1.41</td>
<td>-2.61</td>
</tr>
<tr>
<td>Average $M_{\text{RNX}}$</td>
<td>0.090 ± 0.009</td>
<td>0.094 ± 0.012</td>
<td>0.35</td>
<td>-0.82</td>
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<tr>
<td>Average $M_{\text{RNE}}$</td>
<td>0.056 ± 0.029</td>
<td>0.149 ± 0.027</td>
<td>2.77</td>
<td>2.13</td>
</tr>
<tr>
<td>Average $M_{\text{RNP}}$</td>
<td>0.145 ± 0.024</td>
<td>0.144 ± 0.019</td>
<td>-0.06</td>
<td>-1.10</td>
</tr>
<tr>
<td>Peak $P_{\text{RNX}}$</td>
<td>0.257 ± 0.050</td>
<td>0.548 ± 0.033</td>
<td>5.81</td>
<td>4.87</td>
</tr>
<tr>
<td>Peak $P_{\text{RNE}}$</td>
<td>0.080 ± 0.050</td>
<td>0.538 ± 0.077</td>
<td>5.94</td>
<td>5.14</td>
</tr>
<tr>
<td>Peak $P_{\text{RNP}}$</td>
<td>0.355 ± 0.079</td>
<td>0.324 ± 0.078</td>
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<td>-1.42</td>
</tr>
<tr>
<td>Average $P_{\text{RNX}}$</td>
<td>0.156 ± 0.025</td>
<td>0.192 ± 0.034</td>
<td>1.02</td>
<td>-0.02</td>
</tr>
<tr>
<td>Average $P_{\text{RNE}}$</td>
<td>0.034 ± 0.023</td>
<td>0.180 ± 0.035</td>
<td>4.21</td>
<td>3.43</td>
</tr>
<tr>
<td>Average $P_{\text{RNP}}$</td>
<td>0.167 ± 0.029</td>
<td>0.144 ± 0.040</td>
<td>-0.57</td>
<td>-1.64</td>
</tr>
</tbody>
</table>

*Note. Acronym identifies MBI: ND = not different, P = possible, L = likely, VL = very likely, AC = almost certain.
Table 5.4 continued

<table>
<thead>
<tr>
<th>Variable</th>
<th>Rear Leg</th>
<th>Front Leg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$H_{PL}$</td>
<td>$H_{FR}$</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>SD</td>
</tr>
<tr>
<td>Peak $M_{Plk}$</td>
<td>0.232 ± 0.024</td>
<td>1.24</td>
</tr>
<tr>
<td>Peak $M_{Plh}$</td>
<td>0.178 ± 0.031</td>
<td>2.17</td>
</tr>
<tr>
<td>Peak $M_{Plp}$</td>
<td>0.334 ± 0.021</td>
<td>1.36</td>
</tr>
<tr>
<td>Average $M_{Plk}$</td>
<td>0.178 ± 0.017</td>
<td>5.23</td>
</tr>
<tr>
<td>Average $M_{Plh}$</td>
<td>0.118 ± 0.022</td>
<td>1.97</td>
</tr>
<tr>
<td>Average $M_{Plp}$</td>
<td>0.236 ± 0.024</td>
<td>3.16</td>
</tr>
<tr>
<td>Peak $P_{Plk}$</td>
<td>0.676 ± 0.144</td>
<td>3.22</td>
</tr>
<tr>
<td>Peak $P_{Plh}$</td>
<td>0.480 ± 0.092</td>
<td>4.50</td>
</tr>
<tr>
<td>Peak $P_{Plp}$</td>
<td>0.383 ± 0.110</td>
<td>0.42</td>
</tr>
<tr>
<td>Average $P_{Plk}$</td>
<td>0.299 ± 0.057</td>
<td>2.73</td>
</tr>
<tr>
<td>Average $P_{Plh}$</td>
<td>0.220 ± 0.043</td>
<td>4.56</td>
</tr>
<tr>
<td>Average $P_{Plp}$</td>
<td>0.268 ± 0.070</td>
<td>1.62</td>
</tr>
</tbody>
</table>
5.3.1.1 Ankle Joint

Very large to extremely large negative differences in joint angle were observed, showing that the front and rear ankle joints were typically operating at greater dorsiflexion in all exercises compared with the block start (Fig. 5.2). Similarity in joint angle was only observed at the rear ankle joint towards the end of movement at the point of peak ankle plantarflexion (Fig. 5.2). Positive and meaningful differences in rear leg peak $M_{\text{ANK}}$ were only observed for $JS_{60}$ ($d = 2.69$, almost certain), $MBD_{\text{SP}}$ ($d = 1.38$, very likely), $HJBL$ ($d = 1.24$, likely), and $HJSP$ ($d = 1.00$, likely) (Table 5.4). The largest difference in rear leg average $M_{\text{ANK}}$ was observed for $HJBL$ ($d = 5.23$, almost certain), with positive and meaningful differences also reported for $JS_{60}$, $BS_{90}$, $HJSP$, $MBD_{\text{BL}}$ and $MBD_{\text{SP}}$ ($d = 1.51$ to $3.59$, very likely to almost certain) (Table 5.4). Peak and average rear $M_{\text{ANK}}$ was not different for $JS0$ ($d = 0.35$). Continuous data highlighted that the initial and final 30% of movement (HJ and MBD), and final 30% (JS and BS$_{90}$) were the locations of greatest difference in comparison to the block start (Fig. 5.3).

All exercises demonstrated positive and meaningful differences in front leg peak $M_{\text{ANK}}$ in comparison with the block start (Table 5.4). Of these, an extremely large positive difference was observed for $JS_{60}$ ($d = 5.83$, almost certain), whilst other very large differences were found for $JS0$, $HJBL$, $HJSP$ and $MBD_{\text{SP}}$ ($d = 2.24$ to $3.28$, almost certain), and a large difference was found for $BS_{90}$ ($d = 1.02$, likely). $HJBL$ and $MBD_{\text{BL}}$ exhibited the largest positive differences in front leg average $M_{\text{ANK}}$ ($d = 3.95$ and $4.85$, almost certain, respectively), followed by $JS_{60}$ and $HJSP$ ($d = 2.58$ and $2.73$, almost certain, respectively) and $MBD_{\text{SP}}$ ($d = 1.53$, very likely). For $JS0$ the magnitude of average $M_{\text{ANK}}$ was deemed not different ($d = -0.16$) (Table 5.4).

At the joint power level, peak and average $P_{\text{ANK}}$ at the front and rear leg were almost certainly smaller in $BS_{90}$ compared with the block start (Table 5.4). For all other exercises, meaningfully greater magnitudes of peak and average $P_{\text{ANK}}$ were observed across both legs, except for rear average $P_{\text{ANK}}$ during $JS_{60}$ (Table 5.4). Effect sizes for ankle power data were typically largest for the $HJBL$ exercise, although $JS0$ possessed the largest effect size for rear peak $P_{\text{ANK}}$ (Table 5.4). For both legs, the magnitude of positive extensor ankle power did not typically exceed that of the block start until 70-80% of block time, at which point very large to extremely large differences were observed (Fig. 5.4).
Figure 5.2. Ensemble group average dorsi-plantar-flexion rear (left) and front (right) ankle joint angle-normalised time histories for the block start (black solid line) and each exercise. Black dotted lines represent block start standard deviation. Colour maps visually represent the standardised effect size difference ($d$) between the block start (BL) and training exercise (Ex). Full colour reference can be found in Table 5.3.
Figure 5.3. Ensemble group average rear (left) and front (right) ankle joint moment-normalised time histories for the block start (black solid line) and each exercise. Black dotted lines represent block start standard deviation. Colour maps visually represent the standardised effect size difference ($d$) between the block start (BL) and training exercise (Ex). Full colour reference can be found in Table 5.3.
Figure 5.4. Ensemble group average rear (left) and front (right) ankle joint power-normalised time histories for the block start (black solid line) and each exercise. Black dotted lines represent block start standard deviation. Colour maps visually represent the standardised effect size difference (d) between the block start (BL) and training exercise (Ex). Full colour reference can be found in Table 5.3.
5.3.1.2 Knee Joint

Greater differences in joint angle between the block start and each training exercise were noted at the rear leg compared with the front (Fig. 5.5). At the front leg, knee joint angle in all training exercises possessed similarity with the block start at the start and end of movement (Fig. 5.5). In general, greater similarity to the block start was seen in the horizontal jump exercises compared with jump squat variations (Fig. 5.5).

All exercises elicited greater magnitudes of rear knee extensor moment and power generation compared with the block start, with differences being at least large and meaningful ($d = 1.94$ to $5.94$, very likely to almost certain) (Table 5.4). The observed differences manifested between 40-90% of movement time whilst the knee joint was generating extensor power in all exercises but was minimal in the block start (Fig. 5.6, 5.7).

In contrast, no exercise possessed a positive meaningful difference in front peak $M_{\text{KNE}}$, with all horizontal plane exercises showing negative effect sizes, and only a possible positive difference observed for BS$_{90}$ ($d = 0.79$) (Table 5.4). Front average $M_{\text{KNE}}$ was likely greater in JS$_{60}$ and BS$_{90}$ compared with the block start ($d = 1.52$ and 1.61, respectively) and possibly greater in JS$_{0}$ ($d = 0.72$). Moderate to large negative differences were found for HJ$_{BL}$, HJ$_{SP}$ and MBD$_{SP}$, whilst average $M_{\text{KNE}}$ was deemed not different between the block start and MBD$_{BL}$ (Table 5.4). Continuous data highlighted that HJ$_{SP}$ and MBD$_{SP}$ exhibited similar magnitudes of front $M_{\text{KNE}}$ compared to the block start throughout the majority of movement (Fig. 5.6). For all other exercises, greater magnitudes of front $M_{\text{KNE}}$ were found during the first 50% of movement time, with JS$_{0}$, JS$_{60}$ and BS$_{90}$ possessing the largest differences (Fig. 5.6).

All exercises elicited temporal similarity in front knee joint power in comparison with the block start, with extensor power generation beginning between 40-50% of movement time (Fig. 5.7). Whilst MBD$_{BL}$ and MBD$_{SP}$ were shown to elicit a possibly greater magnitude of average $P_{\text{KNE}}$ compared with the block start ($d = 0.78$ and 0.80, respectively), no exercise was able to elicit a meaningful positive difference in peak or average $P_{\text{KNE}}$ (Table 5.4).
Figure 5.5. Ensemble group average flexion-extension rear (left) and front (right) knee joint angle-normalised time histories for the block start (black solid line) and each exercise. Black dotted lines represent block start standard deviation. Colour maps visually represent the standardised effect size difference ($d$) between the block start (BL) and training exercise (Ex). Full colour reference can be found in Table 5.3.
Figure 5.6. Ensemble group average rear (left) and front (right) knee joint moment-normalised time histories for the block start (black solid line) and each exercise. Black dotted lines represent block start standard deviation. Colour maps visually represent the standardised effect size difference ($d$) between the block start (BL) and training exercise (Ex). Full colour reference can be found in Table 5.3.
Figure 5.7. Ensemble group average rear (left) and front (right) knee joint power-normalised time histories for the block start (black solid line) and each exercise. Black dotted lines represent block start standard deviation. Colour maps visually represent the standardised effect size difference ($d$) between the block start (BL) and training exercise (Ex). Full colour reference can be found in Table 5.3.
Although no positive meaningful differences were found at the group level, individual effect sizes revealed several instances in which a training exercise elicited a meaningfully greater magnitude of knee joint power compared with the block start (Table 5.5). For the lowest ranked athlete (athlete Q), positive and meaningful differences for all exercises aside from BS\(_{90}\) were found for both peak and average P\(_{KNE}\) (Table 5.5). Conversely, athlete N showed consistent negative and meaningful differences for all knee power data, whilst athlete G exhibited a mix of negative and no differences (Table 5.5). Across the rest of the athletes (athlete K, L, M), several positive and meaningful differences were detected for peak and average P\(_{KNE}\) across exercises JS\(_{0}\), JS\(_{60}\), HJ\(_{BL}\), MBD\(_{BL}\) and MBD\(_{SP}\).

Table 5.5. Individual effect size (d) data for comparisons between each exercise and the block start for front leg peak and average knee extensor power generation (P\(_{KNE}\)).

<table>
<thead>
<tr>
<th>Athlete</th>
<th>JS(_{0})</th>
<th>JS(_{60})</th>
<th>BS(_{90})</th>
<th>HJ(_{BL})</th>
<th>HJ(_{SP})</th>
<th>MBD(_{BL})</th>
<th>MBD(_{SP})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak P(_{KNE})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>-1.50</td>
<td>-3.66</td>
<td>-6.18</td>
<td>-2.08</td>
<td>-1.87</td>
<td>-1.19</td>
<td>-0.52</td>
</tr>
<tr>
<td>K</td>
<td>-1.79</td>
<td>-5.01</td>
<td>-8.04</td>
<td>-3.04</td>
<td>-3.42</td>
<td>-1.27</td>
<td>-2.19</td>
</tr>
<tr>
<td>L *</td>
<td>3.00</td>
<td>2.34</td>
<td>-0.53</td>
<td>1.12</td>
<td>0.62</td>
<td>0.84</td>
<td>2.39</td>
</tr>
<tr>
<td>M</td>
<td>-1.81</td>
<td>-5.36</td>
<td>-18.20</td>
<td>2.31</td>
<td>0.03</td>
<td>0.35</td>
<td>2.67</td>
</tr>
<tr>
<td>N</td>
<td>-6.36</td>
<td>-6.37</td>
<td>-10.11</td>
<td>-10.03</td>
<td>-6.26</td>
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<td>-8.24</td>
</tr>
<tr>
<td>Q *</td>
<td>4.37</td>
<td>3.40</td>
<td>-0.23</td>
<td>3.02</td>
<td>2.35</td>
<td>3.90</td>
<td>2.78</td>
</tr>
<tr>
<td>Average P(_{KNE})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>-1.62</td>
<td>-4.52</td>
<td>-5.41</td>
<td>-0.41</td>
<td>-0.60</td>
<td>0.14</td>
<td>0.20</td>
</tr>
<tr>
<td>K *</td>
<td>0.83</td>
<td>-2.42</td>
<td>-3.24</td>
<td>0.14</td>
<td>0.43</td>
<td>4.16</td>
<td>4.17</td>
</tr>
<tr>
<td>L *</td>
<td>2.80</td>
<td>0.20</td>
<td>-0.80</td>
<td>2.78</td>
<td>1.41</td>
<td>3.55</td>
<td>3.29</td>
</tr>
<tr>
<td>M *</td>
<td>-4.00</td>
<td>-9.33</td>
<td>-19.64</td>
<td>1.24</td>
<td>0.34</td>
<td>2.25</td>
<td>7.56</td>
</tr>
<tr>
<td>Q *</td>
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<td>2.00</td>
<td>-0.04</td>
<td>4.21</td>
<td>3.41</td>
<td>5.76</td>
<td>3.13</td>
</tr>
</tbody>
</table>

Note: * indicates athlete where positive meaningful differences were shown (at least likely moderate).
5.3.1.3 Hip Joint

For HJ\textsubscript{SP} and MBD\textsubscript{SP}, rear hip angle at movement onset was similar to that during the block start, whereas for all bilateral exercises the rear hip was placed in greater flexion (Fig. 5.7). At the end of movement, all exercises promoted a more extended rear hip joint angle compared to the block start (Fig. 5.8). At the front leg, similarity in hip joint angle between all exercises and the block start was observed across all exercises during the first 40% of movement time (Fig. 5.8). In contrast to the rear leg, front hip angle was more flexed at the end of movement during all exercises compared to the block start (Fig. 5.8).

The greatest magnitudes of front and rear leg peak and average \textit{M}_{\textit{HIP}} were found for BS\textsubscript{90}, and were likely to almost certainly larger compared with the block start (d = 1.05 to 3.97, respectively) (Table 5.4). Other positive meaningful differences in rear leg peak and average \textit{M}_{\textit{HIP}} were found for JS\textsubscript{60} (d = 1.17, likely and 2.95, very likely, respectively) and HJ\textsubscript{BL} (d = 1.36, very likely and 3.97, almost certain, respectively), with MBD\textsubscript{BL} showing a positive meaningful difference in average \textit{M}_{\textit{HIP}} (d = 1.03, likely) (Table 5.4). For MBD\textsubscript{SP} and JS\textsubscript{0}, negative differences in rear peak \textit{M}_{\textit{HIP}} were found, although no differences in average \textit{M}_{\textit{HIP}} were found (Table 5.4). Magnitudes of difference in rear \textit{M}_{\textit{HIP}} were very large to extremely large at movement onset for all exercises, with a second period of very large positive difference observed in JS\textsubscript{60} and BS\textsubscript{90} between 70-90% of movement time (Fig. 5.9).

Aside from BS\textsubscript{90}, no other exercise elicited a meaningful positive difference in front peak \textit{M}_{\textit{HIP}}, with all other comparisons deemed not different (HJ\textsubscript{BL} and HJ\textsubscript{SP}) or likely to almost certainly negative (JS\textsubscript{0}, MBD\textsubscript{BL}, and MBD\textsubscript{SP}). Front leg average \textit{M}_{\textit{HIP}} was likely smaller in JS\textsubscript{0} (d = -1.47), not different in MBD\textsubscript{BL} and MBD\textsubscript{SP}, and meaningfully greater in JS\textsubscript{60} (d = 1.75, likely), HJ\textsubscript{BL} (d = 1.32, likely), HJ\textsubscript{SP} (d = 1.62, very likely), and BS\textsubscript{90} (d = 2.16, almost certain) compared with the block start (Table 5.4). In a similar way to the rear leg, a local period of very large and extremely large effect sizes during the first 20% of movement were observed in all exercises, followed by a second period in JS\textsubscript{60} and BS\textsubscript{90} from 60% onwards (Fig. 5.9).
Figure 5.8. Ensemble group average flexion-extension rear (left) and front (right) hip joint angle-normalised time histories for the block start (black solid line) and each exercise. Black dotted lines represent block start standard deviation. Colour maps visually represent the standardised effect size difference (d) between the block start (BL) and training exercise (Ex). Full colour reference can be found in Table 5.3.
Figure 5.9. Ensemble group average rear (left) and front (right) hip joint moment-normalised time histories for the block start (black solid line) and each exercise. Black dotted lines represent block start standard deviation. Colour maps visually represent the standardised effect size difference ($d$) between the block start (BL) and training exercise (Ex). Full colour reference can be found in Table 5.3.
Figure 5.10. Ensemble group average rear (left) and front (right) hip joint power-normalised time histories for the block start (black solid line) and each exercise. Black dotted lines represent block start standard deviation. Colour maps visually represent the standardised effect size difference ($d$) between the block start (BL) and training exercise (Ex). Full colour reference can be found in Table 5.3.
With respect to hip joint power, HJ_{BL} was the only exercise able to elicit a positive meaningful difference, and was found for rear average P_{HIP} (\(d = 1.62\), likely) (Table 5.4). All other differences at the rear and front leg were either negative in magnitude or considered not meaningfully different. Continuous data revealed that HJ_{BL} elicited the greatest magnitude of rear P_{HIP} during the first 20% of movement, demonstrating large to very large positive differences (Fig. 5.10). The largest differences in front hip power were observed when the hip was absorbing extensor power in the block start, otherwise hip power was generally lower in all exercises between 20-60% of movement time (Fig. 5.10).

5.4.2 Movement Dynamics (intra-limb joint coordination & variability)
Coupling angle difference (CA\textsubscript{DIF}) for all joint couples are presented in Table 5.6, with Figures 5.11-5.13 detailing coupling angle profiles across the normalised time cycle for the block start and each exercise. Overall, CA\textsubscript{DIF} was typically higher for the K-A joint couple across both legs, and at the front leg, typically lower for exercises performed from a bilateral stance (Table 5.6). Adopting a split stance appeared to reduce the magnitude of CA\textsubscript{DIF} at the rear leg only (Table 5.6).

Table 5.6. Group mean (and individual range) coupling angle difference (CA\textsubscript{DIF} %) between the block start and each exercise, for the hip-knee (H-K), hip-ankle (H-A), and knee-ankle (K-A) joint couples.

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Rear Leg CA\textsubscript{DIF} (%)</th>
<th>Front Leg CA\textsubscript{DIF} (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JS\textsubscript{60}</td>
<td>17 (18)</td>
<td>20 (13)</td>
</tr>
<tr>
<td>JS\textsubscript{90}</td>
<td>23 (23)</td>
<td>18 (12)</td>
</tr>
<tr>
<td>BS\textsubscript{90}</td>
<td>18 (27)</td>
<td>20 (12)</td>
</tr>
<tr>
<td>HJ\textsubscript{BL}</td>
<td>34 (15)</td>
<td>20 (6)</td>
</tr>
<tr>
<td>HJ\textsubscript{SP}</td>
<td>27 (18)</td>
<td>18 (16)</td>
</tr>
<tr>
<td>MBD\textsubscript{BL}</td>
<td>37 (19)</td>
<td>17 (9)</td>
</tr>
<tr>
<td>MBD\textsubscript{SP}</td>
<td>22 (34)</td>
<td>11 (8)</td>
</tr>
</tbody>
</table>
5.3.2.1 Hip-Knee Coordination (H-K)

Lower magnitudes of CA\textsubscript{DIF} for rear leg H-K coordination were typically observed for the squat variations (17% to 23%) compared with the horizontal jump exercises (22% to 37%) (Table 5.6). Larger CA\textsubscript{DIF} values for the horizontal jump exercises resulted from greater differences in coordination patterns from 0-30% of movement time (Fig. 5.11). Following 50% of movement time, all exercises adopted the same coordination pattern and therefore differences in coordination with respect to the block start were consistent across all exercises (Fig. 5.11). Adopting a split stance reduced the magnitude of CA\textsubscript{DIF} (Table 5.6), by reducing the magnitude and frequency of differences during the first 50% of movement (Fig. 5.11). At the front leg, CA\textsubscript{DIF} ranged from 8% in JS\textsubscript{60} to 21% in MBD\textsubscript{SP}, with all exercises showing lower front leg values compared to the rear leg (Table 5.6). Continuous analysis (Fig. 5.11) again revealed that inter-exercise differences in front leg H-K coordination was most apparent in the early stages of movement. Following 50% of movement time all exercises elicited the same pattern of in phase extension coordination as demonstrated in the block start (Fig. 5.11).

5.3.2.2 Hip Ankle Coordination (H-A)

Similar front leg H-A CA\textsubscript{DIF} was observed across most exercises (7% to 10%) but was higher for MBD\textsubscript{SP} (15%) (Table 5.6). Again, it was the onset of movement where the greatest differences in joint coordination patterns were observed (Fig. 5.12). For bilateral exercises, these initial differences in front leg CA\textsubscript{DIF} were a result of an earlier transition between anti-phase and proximal extension coordination patterns. However, for HJ\textsubscript{SP} and MBD\textsubscript{SP} a distinct period of distal flexion was present at the start of movement as the front ankle joint underwent flexion and the front hip joint angle remained relatively unchanged (Fig. 5.12). After approximately 30% of movement time, all exercises elicited similar front H-A coordination compared to the block start, by transitioning through proximal extension and in-phase extension patterns (Fig. 5.12). At the rear leg, the lowest CA\textsubscript{DIF} in H-A coordination was found for MBD\textsubscript{SP} (11%) with CA\textsubscript{DIF} in all other exercises ranging from 17% (MBD\textsubscript{BL}) to 20% (JS\textsubscript{0}, BS\textsubscript{90}, HJ\textsubscript{BL}) (Table 5.6). During the second half of movement, rear H-A coordination in the block start was more distal (ankle) dominant in comparison to the training exercises (Fig. 5.12).
Figure 5.11. Group average rear (left) and front (right) hip-knee (H-K) joint coordination time histories for the block start (black circles) and each exercise. Colour maps visually represent the ‘difference score’ (right legend) in coordination classification with respect to the block start (Fig. 5.1).
Figure 5.12. Group average rear (left) and front (right) hip-ankle (H-A) joint coordination time histories for the block start (black circles) and each exercise. Colour maps visually represent the ‘difference score’ (right legend) in coordination classification with respect to the block start (Fig. 5.1).
5.3.2.3 Knee Ankle Coordination (K-A)

Of all joint couples, \( \text{CADIF} \) values were typically larger for K-A joint coordination (Table 5.6). In a similar fashion to H-K joint coordination, \( \text{CADIF} \) was typically lower in the squat variations compared with the horizontal jumps and in the front leg compared with the rear (Table 5.6). Continuous analysis once more revealed that the inter-exercise differences in \( \text{CADIF} \) was mainly determined from the initial 40% of movement time, although K-A coordination for both limbs during BS\(_{90} \) showed greater differences during the second half of movement compared with all other exercises (Fig. 5.13). Adopting a split stance during HJ and MBD increased K-A coordination similarity with the block start at the rear leg, by reducing differences during the first 50% of movement compared with their bilateral counterparts (Fig. 5.13).

5.3.2.4 Individual Responses

Within-athlete \( \text{CADIF} \) data revealed individual magnitudes of change in response to adopting a split stance during the HJ and MBD exercise. (Table 5.7). At the rear leg, the general trend was aligned with that of the group level results (Table 5.6) in that a reduction (negative value) in \( \text{CADIF} \) for all joint couples was observed when adopting a split stance (Table 5.7). However, the magnitude of this response was influenced by the individual athlete, and increases in \( \text{CADIF} \) were observed for athletes L and G for the H-K and H-A joint couples, respectively, for the HJ exercise (Table 5.7). At the front leg, individual results were mostly aligned with that of the group results (Table 5.6), in that an increase in \( \text{CADIF} \) was observed when adopting a split stance during the MBD exercise. However, athletes N and Q observed decreases in \( \text{CADIF} \) for the K-A joint couple between MBD\(_{SP} \) and MBD\(_{BL} \) exercises (Table 5.7).

Overall, the K-A joint couple demonstrated the largest variation in the magnitude of change between bilateral and split stance comparisons (Table 5.7). For example, at the rear leg, difference of -9% (athletes L and N) and -30% (athlete M) were observed when adopting a split stance during the HJ exercise. Conversely, for the same joint couple, athlete M demonstrated the smallest change in \( \text{CADIF} \) between MBD\(_{SP} \) and MBD\(_{BL} \) (-6%), whereas athlete N showed the greatest magnitude of change (-22%).
Figure 5.13. Group average rear (left) and front (right) knee-ankle (K-A) joint coordination time histories for the block start (black circles) and each exercise. Colour maps visually represent the ‘difference score’ (right legend) in coordination classification with respect to the block start (Fig. 5.1).
Table 5.7. Individual changes in CA\textsubscript{DIF} (%) between horizontally projected ballistic exercises performed with a bilateral (HJ\textsubscript{BL}, MBD\textsubscript{BL}) and split stance (HJ\textsubscript{SP}, MBD\textsubscript{SP}). Direction of change indicates a decrease (negative) or increase (positive) in CA\textsubscript{DIF} (%) during the split stance variation.

<table>
<thead>
<tr>
<th>Athlete</th>
<th>HJ\textsubscript{SP} - HJ\textsubscript{BL}</th>
<th>MBD\textsubscript{SP} - MBD\textsubscript{BL}</th>
<th>HJ\textsubscript{SP} - HJ\textsubscript{BL}</th>
<th>MBD\textsubscript{SP} - MBD\textsubscript{BL}</th>
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<tr>
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<td>-17</td>
<td>4</td>
<td>11</td>
</tr>
<tr>
<td>K</td>
<td>-10</td>
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</tr>
<tr>
<td>L</td>
<td>3</td>
<td>-16</td>
<td>-3</td>
<td>10</td>
</tr>
<tr>
<td>M</td>
<td>-8</td>
<td>-3</td>
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<td>11</td>
</tr>
<tr>
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<td>6</td>
</tr>
<tr>
<td>Q</td>
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<td>-10</td>
<td>1</td>
<td>5</td>
</tr>
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</tr>
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<td>K</td>
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5.3.2.5 Joint Coordination Variability

Variability in joint coordination across the entire movement cycle was generally similar between the block start and all exercises, with only few differences reaching at least a ‘likely’ difference. At the rear leg, two large effect sizes were noted and were both for JS\textsubscript{60} (H-K, $d = 1.22$, likely; K-A, $d = 1.17$, likely). Meaningful differences for front leg CA\textsubscript{V} were mainly limited to the squat type exercises and the H-K and H-A joint couples, in which these exercises elicited a greater magnitude of CA\textsubscript{V} compared with the block start (Table 5.8). During the first 20% of movement, the magnitude of coordination variability was generally similar across all joint couples and limbs for the HJ and MBD exercises. Conversely, the majority of differences for CA\textsubscript{V20} were positive and meaningful for all squat variations, indicating a greater magnitude of CA\textsubscript{V} in JS\textsubscript{60}, JS\textsubscript{60} and BS\textsubscript{90} compared to the block start during the initial 20% of movement (Table 5.8).
Table 5.8. Group mean (±) SD joint coordination variability across the entire movement (CAv) and first 20% of movement time (CAv20) for the hip-knee (H-K), hip-ankle (H-A) and knee-ankle (K-A) joint couples at the rear and front leg. Standardised effect sizes (d) and 90% confidence intervals (CI) for comparisons between the block start and each exercise are shown. Inferences are based on the likelihood of the true value of d being moderate (0.6 or -0.6).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Block Start</th>
<th>Jv</th>
<th>CAy</th>
<th>JSy</th>
<th>Jv</th>
<th>CAy</th>
<th>JSy</th>
<th>BSy</th>
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<td>mean</td>
<td>SD</td>
<td>mean</td>
<td>SD</td>
<td>mean</td>
</tr>
<tr>
<td>H-K CAy</td>
<td>7.153 ± 1.554</td>
<td>8.810 ± 3.308</td>
<td>0.54 -0.17 1.25</td>
<td>d</td>
<td>11.282 ± 3.734</td>
<td>1.22 0.57 1.86</td>
<td>L</td>
<td>11.939 ± 6.180</td>
</tr>
<tr>
<td>H-K CAy20</td>
<td>11.165 ± 5.745</td>
<td>28.935 ± 15.421</td>
<td>1.29 0.37 2.20</td>
<td>L</td>
<td>29.062 ± 16.271</td>
<td>1.24 0.52 1.95</td>
<td>L</td>
<td>26.179 ± 9.230</td>
</tr>
<tr>
<td>H-A CAy</td>
<td>7.281 ± 2.668</td>
<td>9.265 ± 3.798</td>
<td>0.51 -0.21 1.23</td>
<td>d</td>
<td>9.565 ± 3.555</td>
<td>0.61 -0.03 1.26</td>
<td>L</td>
<td>11.500 ± 5.850</td>
</tr>
<tr>
<td>H-A CAy20</td>
<td>14.854 ± 6.181</td>
<td>31.022 ± 11.441</td>
<td>1.48 0.73 2.23</td>
<td>P</td>
<td>24.657 ± 15.766</td>
<td>0.69 -0.31 1.69</td>
<td>P</td>
<td>22.561 ± 9.298</td>
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<tr>
<td>K-A CAy</td>
<td>8.916 ± 2.909</td>
<td>11.269 ± 5.826</td>
<td>0.43 -0.29 1.15</td>
<td>P</td>
<td>14.228 ± 4.583</td>
<td>1.17 0.41 1.92</td>
<td>L</td>
<td>13.654 ± 7.651</td>
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<tr>
<td>K-A CAy20</td>
<td>18.086 ± 6.943</td>
<td>31.278 ± 17.291</td>
<td>0.84 -0.10 1.79</td>
<td>d</td>
<td>32.934 ± 16.191</td>
<td>1.00 0.43 1.57</td>
<td>L</td>
<td>30.298 ± 10.510</td>
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<tr>
<td></td>
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<td>mean</td>
<td>SD</td>
<td>mean</td>
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<td>mean</td>
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<tr>
<td>H-K CAy</td>
<td>5.110 ± 0.881</td>
<td>10.994 ± 3.586</td>
<td>1.90 1.13 2.66</td>
<td>VL</td>
<td>11.264 ± 5.081</td>
<td>1.42 0.48 2.36</td>
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<td>17.386 ± 11.324</td>
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<tr>
<td>H-K CAy20</td>
<td>13.291 ± 3.635</td>
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<td>1.89 0.64 2.95</td>
<td>VL</td>
<td>33.629 ± 19.062</td>
<td>1.23 0.16 2.27</td>
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<td>H-A CAy</td>
<td>6.297 ± 0.994</td>
<td>11.999 ± 4.113</td>
<td>1.60 0.56 2.65</td>
<td>L</td>
<td>10.665 ± 4.303</td>
<td>1.18 0.15 2.20</td>
<td>L</td>
<td>16.465 ± 10.461</td>
</tr>
<tr>
<td>H-A CAy20</td>
<td>15.123 ± 5.089</td>
<td>42.387 ± 12.803</td>
<td>2.36 1.55 3.17</td>
<td>AC</td>
<td>33.531 ± 18.354</td>
<td>1.15 0.03 2.27</td>
<td>L</td>
<td>24.258 ± 8.959</td>
</tr>
<tr>
<td>K-A CAy</td>
<td>11.015 ± 1.918</td>
<td>12.492 ± 3.557</td>
<td>0.44 -0.55 1.42</td>
<td>P</td>
<td>15.392 ± 5.823</td>
<td>0.85 -0.35 2.05</td>
<td>P</td>
<td>21.650 ± 10.380</td>
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<td>20.036 ± 10.484</td>
<td>37.005 ± 15.382</td>
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<td>L</td>
<td>35.374 ± 16.485</td>
<td>0.94 -0.32 2.19</td>
<td>P</td>
<td>34.602 ± 11.385</td>
</tr>
</tbody>
</table>

*Note. Acronym identifies MBI: ND = not different, P = possible, L = likely, VL = very likely, AC = almost certain.
Table 5.8 continued.

<table>
<thead>
<tr>
<th>Variable</th>
<th>$\text{H}_{167}$</th>
<th>$\text{H}_{199}$</th>
<th>$\text{MBD}_{\text{ca}}$</th>
<th>$\text{MBD}_{\text{v}}$</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>SD</td>
<td>d</td>
<td>CI-</td>
</tr>
<tr>
<td>Rear Leg</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>H-K CA$\text{v}$</td>
<td>5.803 ± 4.901</td>
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<td>-1.21</td>
<td>0.59</td>
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<td>H-K CA$\text{v}$</td>
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<td>-0.79</td>
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</tr>
<tr>
<td>H-A CA$\text{v}$</td>
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<td>-0.57</td>
<td>-1.60</td>
<td>0.47</td>
</tr>
<tr>
<td>H-A CA$\text{v}$</td>
<td>9.057 ± 6.755</td>
<td>-0.75</td>
<td>-1.64</td>
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<td>K-A CA$\text{v}$</td>
<td>14.402 ± 7.627</td>
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<td>H-A CA$\text{v}$</td>
<td>19.437 ± 14.798</td>
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<td>-0.92</td>
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</tr>
<tr>
<td>Front Leg</td>
<td></td>
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</tr>
<tr>
<td>H-K CA$\text{v}$</td>
<td>7.617 ± 6.945</td>
<td>0.43</td>
<td>-0.63</td>
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<td>H-K CA$\text{v}$</td>
<td>12.924 ± 8.965</td>
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<td>-1.24</td>
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<tr>
<td>H-A CA$\text{v}$</td>
<td>8.616 ± 8.437</td>
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<td>H-A CA$\text{v}$</td>
<td>17.061 ± 16.718</td>
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<td>13.339 ± 8.034</td>
<td>-0.59</td>
<td>-1.72</td>
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</tr>
</tbody>
</table>
5.5 Discussion
For athletes who have had exposure to strength training, it is likely that an interaction between the principles of overload and specificity will lead to physiological adaptation that can transfer to improved performance (Cormie et al., 2011b; Siff & Verkoshansky, 1999; Stone, 2002; Young, 2006). Therefore, Chapter 5 has compared both single joint kinematic and kinetics (musculoskeletal demand), and inter-joint coordination and variability (movement dynamics) between the block start and a range of strength training exercises, in order to further develop understanding of the principles of training and appropriate exercise selection.

Key results highlighted that all exercises promoted front leg in-phase extension coordination patterns that were similar to those exhibited in the block start, and the major source of inter-exercise differences were attributed to movement onset. Manipulating task constraints during the horizontal jumps by adopting a split stance, increased coordination similarity with the block start for the rear leg only. In general, coordination variability was found to be of greater magnitude in vertical tasks compared with the block start, and of similar magnitude during horizontal tasks. Joint kinetic analyses highlighted that most exercises elicited overload in ankle plantarflexion moment and power generation, although in each training exercise both ankle joints were more dorsiflexed compared with the block start. Exercises with additional external load (JS₆₀, BS₉₀) were most effective at overloading extensor moment demand at the knee and hip joints, although local overload at the onset of movement was demonstrated across most other exercises.

Whilst no exercise was able to elicit a positive meaningful difference in hip extensor power generation, meaningfully greater magnitudes of front knee extensor power generation were shown across several exercises when analysed on an individual level. Finally, no exercise was able to replicate the specific function of the rear knee joint that was highlighted in Chapter 3. Overall, results suggested that globally determining the most effective training exercises is complex, and exercise selection should consider the desired adaptation, biomechanical determinants of performance, and individual athlete.

5.5.1 Musculoskeletal Demand
Training theory dictates that a training exercise must provide a heightened physiological stimulus compared with a competition task (overload) in order for
neuromuscular adaptation to occur (Selye, 1936; 1951). Joint kinetic analysis provides information pertaining to the fundamental causes of movement and the muscular effort required (Winter, 2009), and can quantify the mechanical demand placed on the muscles responsible for executing a task so that the nature of potential adaptations can be understood. Consideration of joint kinetic data alongside joint angle information is pertinent to understand the functionality of an overload stimulus with respect to the block start, as many investigations have detailed that adaptations to strength training are joint angle specific (Morrissey et al., 1995). Ensuring a functional level of musculoskeletal overload, targeted towards the key determinants of competitive performance, may favourably alter organismic constraints (Newell, 1986) that enhance the neuromuscular potential of an athlete to perform a competitive motor task (Verkoshansky, 2011). By comparing individual joint kinematic and kinetic data between the block start and a range of training exercises, the efficacy of these exercises to effectively overload the key musculoskeletal requirements of the competitive motor task could be obtained.

5.5.1.1 Ankle Joint

For both legs, all exercises except JS0 exhibited greater magnitudes of ankle plantarflexor moment in comparison with the block start, at distinct periods across the normalised time cycle (Table 5.4, Fig. 5.3). In both legs, peak $M_{ANK}$ was greatest for JS60, whilst the horizontally projected exercises typically elicited greater magnitudes of average $M_{ANK}$ compared with the squat variations, with HJBL possessing the largest standardised effect size difference (Table 5.4). As peak and average $M_{ANK}$ possessed the strongest relationships with the magnitude of horizontal force applied to each block, and average rear $M_{ANK}$ was one of the key determinants of overall block performance (Chapter 3; Brazil et al., 2018), the observed overload can be considered specific to the biomechanical determinants of block performance. However, different temporal characteristics of overload were demonstrated between vertical and horizontal exercises (Fig. 5.3).

Typically, the horizontal jumps elicited their greatest overload at the beginning of movement, during which the ankle plantarflexor moment was resisting dorsiflexion (Fig. 5.2, 5.3). An overload stimulus during dorsiflexion could be relevant to block performance by increasing ankle stiffness. Increased ankle stiffness could increase block performance through: a reduction in block time by shortening the reversal time between dorsi and plantarflexion (Guissard et al., 1992; Kuitunen, Komi, &
Kyröläinen., 2002), improved force transmission from the hip extensors into the blocks (Cavagna, 1997), or improved horizontal orientation of the resultant force vector (Rabita et al., 2015). The nature of overload was dissimilar in JS_{60}, in which plantarflexion moments only became meaningfully greater after 60% of movement time, when the ankle joint began to extend (Fig. 5.2, 5.3).

The observed larger plantarflexor moments compared with the block start could be explained by the increased magnitude of ankle dorsiflexion from each exercise (Fig. 5.2), altering the force-length properties of the plantarflexor musculature. Previous work has shown increases in isolated plantarflexion torque with increased dorsiflexion up to 40° (Anderson, Madigan, & Nussbaum, 2007; Hahn, Olvermann, Ritchberg, Seiberl, & Scqirtz, 2011; Sale, Quinlan, Marsh, McComas, & Belanger, 1982), which corresponds with joint angles observed in the current study (Fig. 5.2). Furthermore, larger plantarflexion moments have been observed during the first ground contact after block exit (normalised values of 0.378-0.452 Bezodis et al., 2014), when the ankle is placed in greater dorsiflexion in comparison to the block start (Debaere et al., 2013).

When considering joint power, all exercises except BS_{90} demonstrated large to extremely large meaningful differences across $P_{ANK}$ data at the front and rear ankle joint (Table 5.4, Fig. 5.4). The order of effect size magnitudes were again dependent on the variable in question, with peak $P_{ANK}$ favouring JS_{90} (rear leg), but average $P_{ANK}$ favouring the horizontally projected exercises. Ultimately, all jump exercises were shown to increase ankle plantarflexion power generation compared with the block start (Table 5.4). Based on the principle of overload (Siff & Verkoshansky, 1999) all exercises could be utilised within an athlete’s training programme to improve the capacity of the ankle plantarflexors to generate power.

The exercises utilised in the current study may facilitate physiological adaptations in the capacity for the ankle plantarflexors to generate extensor moments and power generation, through the principle of overload (Matveyev, 1981; Dick, 2002; Siff & Verkoshansky, 1999). However, the efficacy of this increased neuromuscular potential to positively transfer to block performance may be threatened by the lack of correspondence in ankle joint angle (Rhea et al., 2016; Siff & Verkoshansky, 1999; Young, 2006). Nonetheless, although increases in strength have been found to be greatest at the angular region promoted in training, some transfer has been
documented outside of the trained range of motion (Graves et al., 1989; Marks, 1994; Rhea et al., 2016). Determining the bandwidth to which adaptations are angle specific during dynamic tasks would be an insightful avenue for future investigation.

### 5.5.1.2 Knee Joint

Chapter 3 highlighted a specific role of the rear knee to stabilise the lower limb and not to generate large magnitudes of extensor power. Unsurprisingly, magnitudes of peak and average $M_{\text{KNE}}$ and $P_{\text{KNE}}$ were very likely to almost certainly greater in all exercises in comparison with the block start (Table 5.4). Altering the task demands of HJ and MBD exercises to replicate the block start did not appear to have an effect of increasing similarity in rear knee joint kinematics and kinetics. Therefore, further investigation is required in order to understand how strength training exercises can be manipulated in order to satisfy the principles of overload and specificity for the task specific function rear knee joint in the block start.

At the front leg, knee extensor moment and power generation has been identified to be meaningfully correlated with the magnitude of horizontal force applied to the front block, with front knee joint $P_{\text{KNE}}$ identified as one of the key determinants of overall block performance (Chapter 3; Brazil et al., 2018). Whilst no exercise could elicit a meaningful positive difference in peak $M_{\text{KNE}}$, $BS_{90}$, $JS_0$ and $JS_{60}$ exhibited moderate to large differences in average $M_{\text{KNE}}$, whereas differences were considered either not different or negative for $HJ_{\text{BL}}$, $HJ_{\text{SP}}$, $MBD_{\text{BL}}$ and $MBD_{\text{SP}}$ (Table 5.4). The occurrence of increased front knee joint extensor moments was at the beginning of movement, when joint angles between the block start and squat variations were in similar magnitudes of flexion (Fig. 5.5). The squat and jump squat exercises may therefore be considered effective exercises for specifically overloading the extensor moment demands of executing the block start (Siff & Verkoshansky, 1999). In addition, increasing the external load might be a strategy to maximise overload of knee extensor moments (Fig. 5.6). The capability of $BS_{90}$ to elicit specific-overload provides biomechanical explanation for why increased maximal squat strength has been shown to be related to sprint acceleration performance (Seitz et al., 2014), and justifies the use of heavy-loaded squat training being implemented into the overall training programme of sprinters (Moir et al., 2018).

At the group level, none of the seven exercise conditions were able to elicit magnitudes of peak $P_{\text{KNE}}$ greater than that observed in the block start, and only
possible positive differences were observed in average $P_{\text{KNE}}$ for MBD$_{\text{BL}}$ and MBD$_{\text{SP}}$ (Table 5.4). Apart from BS$_{90}$, all other exercises appeared to replicate the musculoskeletal demand to generate knee extensor power in the block start (Fig. 5.7). The greater external load in JS$_{60}$ compared with JS$_{0}$ appeared to reduce knee joint extensor power generation, supporting that lower external loads maximise knee extensor power in jump squats (Jandacka et al., 2014). However, individual analyses revealed several positive and meaningful differences in peak and average $P_{\text{KNE}}$ (Table 5.5), and were distributed across both vertical and horizontal jump exercises. The exercise with greatest potential to improve knee extensor power was thus individual dependent, supporting the emergence of individual biomechanical strategies when performing the same task (Bradshaw et al., 2007; Dufek & Bates, 1990), and the importance of considering individual biomechanical strategies for determining optimal training practices (Marián, Katarína, Dávid, Matúš, & Simon; 2016; Morin & Samozino, 2016; Sarabia, Moya-Ramón, Hernández-Davó, Fernandez-Fernandez, & Sabido).

5.5.1.3 Hip Joint

Magnitudes of peak and average $M_{\text{HIP}}$ at both legs were found to be greatest in BS$_{90}$ (Table 5.4) and were higher than that generated in the block start for the majority of movement time (Fig. 5.9). As peak and average $M_{\text{HIP}}$ for both legs was found to be related to the magnitude of horizontal force applied to each block, and average front $M_{\text{HIP}}$ emerged as one of the key determinants of NAHP (Chapter 3; Brazil et al., 2018), BS$_{90}$ can be considered to elicit relevant musculoskeletal overload to the biomechanical determinants of performance. By overloading a key feature of the block start, BS$_{90}$ could be considered specific to the competitive motor task (Moir et al., 2018), although in most literature, BS$_{90}$ would be considered non-specific to sprinting (Crick, 2009; Rumpf et al., 2016; Wild et al., 2011; Young et al., 2001).

When inspecting continuous data, a local period of extensor moment overload at the beginning of movement was identified for all exercises, and again towards the end of movement in JS$_{60}$ and BS$_{90}$ (Fig. 5.9). At the rear leg, adopting a split stance increased the similarity in hip joint angle compared to the block start, whereas in all other exercises greater hip flexion was observed (Fig. 5.8). Therefore, with respect to the rear hip joint, HJ$_{\text{SP}}$ appeared to elicit the most specific overload stimulus at the onset of movement (Siff & Verkoshansky, 1999). At the front leg, all exercises shared similarity in hip joint angle during the first 20% of movement when extensor
moments were larger than the block start, making it difficult to conclude the most effective exercise at eliciting sport specific adaptations in hip extensor strength.

Increasing hip extensor strength at the beginning of movement may positively affect block performance by increasing the magnitude of force applied to the blocks during the initial rise in the force-time curve and contribute towards greater magnitudes of average $F_Y$ (Willwacher et al., 2016). Furthermore, increased hip extensor strength to extend the thigh segments at the beginning of the block start would decrease the time taken to rotate the centre of mass into a position that knee and ankle extension can contribute towards horizontal power generation. In turn, this would minimise block time, which is a governing factor of block performance (Willwacher et al., 2016). With respect to the principle of overload (Matveyev, 1981; Dick, 2002; Siff & Verkoshansky, 1999; Stone et al., 2002), the large to extremely large positive differences in hip extensor moments at the onset of movement (Fig. 5.9), suggest that all may be effective at developing hip extensor strength that is functional to block start performance. However, the decreased effect size magnitude for JS0 and MBDSP suggest that these could be least effective (Fig. 5.9).

Interestingly, effect size differences for hip extensor moments at the beginning of movement were similar between exercises with and without external load (Fig. 5.9). This can be explained in HJBL and HJSP by the presence of a preceding countermovement requiring a hip extensor moment to reverse hip flexion into extension, a common distinction between jumps performed with and without a countermovement (Bobbert et al., 1996). The implication of this finding to exercise selection is that perception of overload (i.e. increasing external resistance) does not always translate into mechanical overload at the joint level, stressing the importance of biomechanical analysis towards informing strength and conditioning practice.

With respect to hip extensor power generation, the HJBL exercise exhibited a large and likely difference in average rear $P_{HIP}$, and was the only meaningful positive difference (Table 5.4). Thus, whilst most exercises were capable of providing a strength stimulus at a specific joint angle (Fig. 5.8, 5.9), they were unable to overload, or match the extensor power generating characteristics of the hip joint during the block start (Table 5.4, Fig. 5.10). This may be considered negative to performance given the dominant role of hip extensor work in the block phase (Chapter 3). However, the stimulus for increased hip extensor strength could be a
precursor to increased power of the hip extensor musculature, as it is known that maximum strength is a determining factor for power generation (Cormie et al., 2011a; Newton & Kraemer, 1994). More research is required into those exercises that can provide a heightened magnitude of hip extensor power in comparison in the block start. The power clean and other Olympic lifts were not considered in the current investigation and could be an interesting avenue for future work given the large demand on hip extensor power generation (Kipp et al., 2016).

5.5.2 Movement Dynamics

Similarity in movement pattern has been widely documented to facilitate the transfer of training and capability for an exercise to enhance competition task performance (McBride et al., 2002; Siff & Verkoshansky, 1999; Wilson et al., 1996, Young, 2006). Coaches often perceive that the time taken to realise neuromuscular adaptations is dependent on the similarity in movement coordination between the training and competitive task (Burnie et al., 2017). This view is supported by the theoretical model established by Bobbert & Van Soest (1994) who found that increases in strength must be accompanied by changes in coordination in order for vertical jump height to increase. From a dynamical systems perspective, the time taken for altered organismic constraints (neuromuscular strength and power) to improve competitive motor task performance, may be influenced by the similarity in coordinative structures between the training and competitive tasks (Davids et al., 2003; Kugler et al., 1980, 1982; Newell et al., 1986).

As coordination patterns emerge through self-organisation within the context of organismic, environmental and task constraints (Newell, 1986), the inherent variability in coordination should be considered to provide an overall analysis of movement dynamics (Hamill et al., 2000). Therefore, in the current study both intra-limb joint coordination patterns and variability were analysed to understand similarity in the dynamical nature of movement. By adopting joint coordination analyses, the current study provided novel insight into the similarity in movement patterns between a competitive motor task and strength training exercises, challenging contemporary views on the features of a ‘specific’ exercise.

For all of the strength training exercises investigated in the current study, closer replication of the emergent coordinative patterns during the block start were shown for the front leg compared with the rear (Table 5.6, Fig. 5.11-5.13). For joint couples
encompassing the knee joint (H-K and K-A) the inter-limb differences in CADIF resulted from the emergence of rear knee flexion in the block start at approximately 50% of movement time, which was not observed in any of the training exercises (Fig. 5.11, 5.13). As a result, rear H-K and K-A joint coordination in the block start transitioned away from an in-phase extension pattern, whereas in-phase extension coordination was dominant during this time for all exercises (Fig. 5.11, 5.13). Higher CADIF values were also reported for the rear leg H-A joint couple compared with the front leg (Table 5.6), and again appeared to result from inter-limb differences in block start coordination following 50% of block time, by which a distal extension pattern prevailed in the block start compared with in-phase extension dominancy in all training exercises (Fig. 5.12).

Inter-exercise differences in coordination patterns were consistently observed at the beginning of movement, and were the main contributing factors to inter-exercise differences in CADIF values (Fig. 5.11-5.13, Table 5.6). The different task constraints for each exercise (Newell, 1986), as well as differences in the changing state of the system at movement onset (Heiderscheit, 2000), likely dictated the early differences in joint coordination patterns.

At the rear leg, the exercises with lowest CADIF were dependent on the joint couple being observed (Table 5.6). For the H-K joint couple, BS90, JS0 and JS60 possessed the lowest CADIF values, whereas CADIF for H-A was similar across all exercises, and for K-A was lowest in JS0, JS60 and MBDSP (Table 5.6). Therefore, it is difficult to elucidate which exercise or groups of exercises were able to closer replicate the global rear leg coordination patterns that manifest in the block start, and inferences can only be made at the level of individual joint couples.

One consistent trend observed was the reduction in rear leg CADIF for HJSP and MBDSP in comparison to their bilateral counterparts (Table 5.6), supporting that task constraints influence emergent patterns of coordination (Newell, 1986). This evidence both supports and questions using visual assessment of posture and direction of movement to suggest movement specificity (Wild et al., 2011). On one hand, manipulating task demands to a split stance in order to closer resemble the block start had the effect of increasing similarity in rear leg coordination patterns, however HJSP and MBDSP did not consistently elicit lower CADIF in comparison to JS0, JS60 and BS90. Furthermore, the response to adopting a split stance was
somewhat dependent on organismic constraints (Newell, 1986) as athletes demonstrated different magnitudes of change between bilateral and split stance variations of the HJ and MBD exercise (Table 5.7).

At the front leg, all exercises settled into similar coordination patterns to the block start after approximately 50% of movement time when an in-phase extension coordination pattern began to emerge (Fig. 5.11-5.13). Similarities were consistent across exercises during this period, although H-A and K-A coordination patterns were more proximal dominant during for BS₉₀ (Fig. 5.12, 5.13). Therefore, in regards to the replication of in-phase extension coordination, all exercises could be considered specific to the nature of the block start (Romanazzi et al., 2015). As in-phase extension coordination was identified as a task specific coordinative structure for block start execution (Chapter 4), replicating this within a training exercise may enhance the potential for an athlete to effectively utilise their neuromuscular potential in the context of the competitive motor task (Bobbert & Van Soest, 1994; Verkoshansky, 2011).

Again, intra-limb joint coordination at the front leg demonstrated that the main source of inter-exercise difference was attributed to the onset of movement (Fig. 5.11-5.13). In particular, the presence of concomitant knee and ankle joint flexion at the beginning of movement in the horizontal jump exercises meant that H-K and K-A coordination were closer replicated in the squat-based exercises (Fig. 5.11, 5.13). However, an earlier phase transition in the squat exercises towards in-phase coordination meant that H-K coordination was closer replicated in the horizontal jump exercises between 30-50% of movement time (Fig. 5.11). Understanding these local changes in coordination is important when seeking to understand the potential effect on competition performance, as it has been previously shown that specific temporal changes in coordination can occur through training (Leirdal & Ettema, 2008).

Manipulating the task demands of the HJ and MBD exercise to a split stance position favoured coordination specificity at the rear leg although the same was not found at the front leg, with CA_{DIF} scores were typically higher in HJ_{SP} and MBD_{SP} compared with their bilateral counterparts (Table 5.6). Again, this evidence highlighted that the appearance of the exercise does not necessarily dictate the interaction between working joints in a multi-linked system, and adopting an inter-joint coordinative
approach to quantifying movement specificity is supported (Irwin & Kerwin, 2007a; Romanazzi et al., 2015; Wilson, 2009).

The inherent variability in inter-joint coordination, resulting from self-organisation of redundant degrees of freedom under imposed constraints (Bernstein, 1967; Newell, 1986), can be considered functional towards performance if it allows the performer to achieve consistent performance outcomes (Bartlett et al., 2007; Preatoni et al., 2013). In the current study, coordination variability ($CA_V$, $CA_{V20}$) was generally higher in JS$_0$, JS$_{60}$ and BS$_{90}$ in comparison to the block start whereas similarity was often shown for the horizontal jump exercises (Table 5.8). As the magnitude of coordination variability has been found not to be related to block performance (Chapter 4), increased $CA_{V20}$ in JS$_0$, JS$_{60}$ and BS$_{90}$ could be interpreted as potentially harmful to performance, and decrease the specificity of these exercises with respect to the block start (Irwin & Kerwin, 2007a). Conversely, promoting a wider landscape of coordinative patterns at the initiation of movement might promote the ability to adapt to changes in neuromuscular potential and/or anthropometrics (organismic constraints), block settings (task constraints), or other environmental constraints (Glazier, 2015; Newell, 1986).

Lower $CA_V$ effect sizes compared to $CA_{V20}$ indicated that for JS$_0$, JS$_{60}$ and BS$_{90}$, consistency in coordination manifested as the movement progressed, in a similar manor observed in the block start (Chapter 4). Thus, allowing a wider range of coordinative solutions to initiate movement but ultimately settle on coordinative structures that are functionally linked to task performance (in-phase extension coordination), could be deemed an encouraging characteristic for promoting adaptable performers producing consistent task outcomes (Glazier & Davids, 2009; Kelso, 1995).

Interestingly, $CA_{V20}$ was greater in the squat exercises compared with the horizontal jumps (Table 5.8), even though the starting position was controlled (more constrained) in the former and self-selected in the latter. A first explanation for this difference could be a result of the specific task constraint during horizontally projected motion to generate both supporting and propelling forces, reducing the degrees of freedom to achieve the task outcome (Newell, 1986). Secondly, the more pronounced state change in the squat exercises (no preliminary movement) may explain higher magnitudes of $CAV_{20}$, as inter-joint coordination is known to be more
variable at transition points when the state of the system is changing (Heiderscheit, 2000; Wilson et al., 2016). Finally, the interaction with external equipment (barbell) may have influenced the self-organisation of coordinative patterns through sensory feedback, to respond to different initial positions of the barbell and maintain optimal positioning in relation to the base of support.

5.5.3 Implications for Exercise Selection

According to the fundamentals of training theory, a specific exercise is one that specifically overloads the musculoskeletal demand of a sports skill through similar movement patterns (Dick, 2002; Matveyev, 1981; Siff & Verkoshansky, 1999; Stone et al., 2002). In practice, the scientific bases of specific adaptations to imposed stress are often misinterpreted and exercises are classified on a spectrum from general to specific based on perceived replication of the competitive motor task (Burnie et al., 2017; Crick, 2009; Wild et al., 2011; Young et al., 2001). The current investigation challenged this view by first demonstrating that inter-joint coordination patterns were often similar across general (BS\textsubscript{90}), specific (HJ\textsubscript{BL} and MBD\textsubscript{BL}), and manipulated exercises to enhance perceived replication (HJ\textsubscript{SP} and MBD\textsubscript{SP}). Secondly, joint kinetic overload varied across each exercise dependent on the biomechanical determinant of performance, and individual athlete, indicating that all exercises could be considered block start specific dependent on the determinant of performance to be targeted.

Integrating the theoretical basis of the principles of training with a dynamical systems approach (Davids et al., 2003; Moir et al., 2018) based on Newell’s model of constraints (Newell, 1986), may provide the best framework to objectify exercise selection. In this framework, the type of exercise (heavy resistance, ballistic, plyometric etc.) would first be selected based on the desired change in organismic constraints (neuromuscular potential) relevant to the individual biological limitations to performance. The exact exercise to be selected would then be based on the replication of sport specific coordinative structures, in order to maximise the potential for altered organismic constraints to be effectively utilised in the context of the competitive motor task (Bobbert & Van Soest, 1994; Verkoshansky, 2011).

5.5.4 Considerations

By combining single joint kinematics and kinetics, and inter-joint coordination and variability, the current study adopted a holistic approach towards quantifying
overload and specificity characteristics of a training exercise with respect to a competitive motor task (block start). Whilst results have highlighted novel information towards the joint kinematic, joint kinetic and coordinative structure correspondence between training exercises and a competitive skill, theoretical and methodological considerations have arisen.

Firstly, the velocity of each movement at the centre of mass and joint level were not considered. Previous evidence has suggested adaptations are velocity specific (Kanehisa & Miyashita, 1983; Morrissey et al., 1995) and therefore training exercises should replicate the joint angular velocity experienced in competition (Okkonen & Hakkinen, 2013). However, much of this work has been conducted on isokinetic dynamometers, which are rarely used as a training tool by elite athletes whose competition movements do not require constant velocity. Other work has suggested that the intention to move explosively, not the actual velocity attained, is more important for neural adaptations that increase force at high velocities (Behm & Sale, 1993; Cronin et al., 2001; Ives & Shelly, 2003). Furthermore, as specificity should be defined within the purpose of an exercise (Dick, 2002), it appeared unnecessary to address joint angular velocity in exercises such as JS$_{60}$ and BS$_{90}$ in which their purpose is not to replicate velocity characteristics of the block start.

A second consideration in the variables selected to understand musculoskeletal demand was the absence of variables such as joint impulse and work. Three primary factors are thought to be responsible for initiating muscle hypertrophy, which is an integral factor for increasing muscular strength: mechanical tension, muscle damage and metabolic stress (Schoenfeld, 2010). Time under tension can influence all three factors (Schoenfeld, 2010; Burd et al., 2012), and so the longer duration of BS$_{90}$ and JS$_{60}$ may have increased time under tension, reflecting superior joint impulse and work done in comparison to the block start. However, Chapter 3 highlighted that the maximum and average magnitude of joint kinetic extensor properties were determining factors of block performance, and so the decision was made to focus upon these key mechanical characteristics.

Training theory provides a theoretical framework to understand how performing a particular training exercise may improve sports performance based on the concept of specific adaptations to imposed stress (Cunanan et al., 2018; Selye, 1936). Whilst biomechanical analysis can provide insight into the potential adaptations that can
occur from a particular exercise and the potential efficacy to improve sports performance, the exact outcome remains unknown. Future work could thus adopt chronic training studies in order to elucidate the most effective exercises for enhancing block start performance and the exact mechanisms through which this occurs. Furthermore, inherent limitations to inverse dynamics procedures mean that the exact function of the muscle-tendon unit and the muscles acting to cause moment and power production cannot be established. Whilst beyond the scope of this project, future research could further the methodology adopted here to understand overload and specificity characteristics at the level of the muscle-tendon unit.

With respect to statistical analysis, Effect sizes were utilised to provide inferences on the magnitude of differences between an exercise and target skill (Batterham & Hopkins, 2006). This procedure provides a standardised difference based on the mean difference and variability in both datasets, and therefore provides a practical way of measuring magnitudes of difference (Hopkins, 2009). However, like conventional inferential statistics used in hypothesis testing ($P$-values), inferences are made based on the likelihood of a difference being a true difference, and can lead to small difference in raw data being deemed meaningful. This was evident in joint angle data (Fig. 5.1, 5.4, 5.7) in which very large and extremely large differences were shown when the raw difference could be 10-20°. Unfortunately, it is not yet known, nor is the focus of this research, to identify what magnitude of difference is considered big enough to elicit physiological adaptation or small enough to ensure adaptations are joint angle specific.

The importance of combining discrete and continuous analysis techniques was highlighted, with local differences in joint kinetics often observed when discrete data indicated that no difference or negative differences existed (Table 5.8). In addition, continuous analyses permitted qualitative insights to the temporal correspondence in inter-joint coordination patterns, revealing similarity in key coordinative structures (in-phase extension coordination) between the block start and all training exercises. Previous work has shown the importance of considering time-series data and utilising data visualisation to convey key messages (Manal & Stanhope, 2004), and should be encouraged within strength and conditioning practices in order to understand the locality of overload and specificity characteristics.
Combining both group and individual analyses allowed the current investigation to acknowledge general trends and individual uniqueness within the analyses of overload and specificity. Previous research has indicated that individual differences can be masked by grouping data (Dufek, & Bates, 1990), as movement is constrained by the individual athlete (Newell, 1986) and individuals can present different biomechanical strategies for executing the same task (Bradshaw et al., 2007). Individual biomechanical strategies were supported in the current study, most pertinently when quantifying the exercises capable of eliciting overload in front knee joint extensor power generation. Therefore, best practice for determining the most effective training exercises within strength and conditioning and athletic development should endeavour to consider individual biomechanical strategies.

5.6 Conclusion

The introduction to this chapter identified two research questions that can be addressed following the current investigation:

**Research Question 8 – How do lower limb joint kinematics and kinetics compare between the block start and traditionally viewed general and more specific training exercises?**

The greatest differences in joint angle between training exercises and the block start were noted at the ankle joint, with greater magnitudes of dorsiflexion emerging for all exercises throughout the majority of movement time. Knee and hip joint angles were closer replicated in the training exercises, especially during movement onset, although the loaded JS$_{60}$ and BS$_{90}$ were unable to elicit a similar magnitude of maximum hip extension as elicited in the front leg in the block start. Adopting a split stance during the horizontal jump and medicine ball dive exercise had its greatest effect of increasing similarity in rear hip joint angle. Differences in joint angle data were not consistent enough to confirm that traditionally viewed more specific exercises were able to replicate the block start to a greater degree than exercises traditionally considered less specific.

Aside from BS$_{90}$, all other exercises were capable of eliciting a greater magnitude of ankle plantarflexion moment and/or power generation, although the largest effect sizes were spread across the remaining exercises based on the variable of interest.
Rear knee joint kinetics were meaningfully greater in all exercises due to the differing mechanical responsibility of this joint between the block start and training exercises. At the front leg, the loaded JS$_{60}$ and BS$_{90}$ exhibited the greatest overload in knee joint moments, although all exercises demonstrated very large to extremely large differences at the beginning of movement. Similar results were shown at the hip joint with positive differences apparent at movement onset for all exercises, although BS$_{90}$ and JS$_{60}$ were able to maintain a higher magnitude of hip extensor moment throughout task execution. All jump exercises were capable of replicating front knee joint extensor power generation, and on an individual bases were capable of producing an overload stimulus for this key characteristic of block start performance. However, no exercise was capable of overloading the magnitude of hip extensor power generation required during the execution of the block start.

**Research Question 9** – How does intra-limb joint coordination and coordination variability compare between the block start and traditionally viewed general and more specific exercises?

Increased similarity in coordination patterns was found for joint coupling at the front leg, due to the dissimilar nature of rear knee joint motion between the block start and each training exercise. Adopting a split stance in order to closer resemble the postures of the block start had the effect of increasing coordination similarity at the rear leg in comparison to their bilateral counterparts, although values of CA$_{DIF}$ were still comparable to those exhibited in the back squat and jump squat exercises. Differences in coordination patterns between each exercise and the block start typically occurred at the onset of movement, however all exercises were able to replicate proximal and in-phase extension coordination patterns emergent in the block start after 50% of movement time. Therefore, all exercises could be considered to replicate this this key coordinative feature of block performance.

The traditionally viewed less specific exercises (JS$_0$, JS$_{60}$ and BS$_{90}$) promoted higher magnitudes of joint coordination variability compared with the block start and horizontal jump exercises. Although the implication of increased CAV is not yet known, it could be attributed to a number of factors including constraints imposed on the task due to external force management, sensory feedback through the environmental constraint of the barbell, or system state changes.
5.7 Chapter Summary
This study has investigated characteristics of musculoskeletal demand and movement dynamics in a range of strength training exercises in relation to the block start, in order to increase knowledge and understanding of the principles of overload and specificity for exercise selection. Inconsistency in the magnitude and direction of joint kinetic differences at the knee and hip joint emphasised the requirement for a mixed-methods approach towards exercise selection (Cormie et al., 2011b), focusing on the biomechanical determinants of performance, so that task-specific improvements in an athlete's motor potential (organismic constraints) can be achieved.

Encompassing inter-joint coordination and variability in a holistic approach revealed that perceived replication of movement did not necessarily translate into replication of coordinative patterns. Adopting a coordinative approach to quantifying the similarity in movement patterns between two tasks continued the work of previous authors (Irwin & Kerwin, 2007a; Romanazzi et al., 2015; Wilson et al., 2009), and emphasised its value towards informing exercise selection. From a dynamical systems perspective (Davids et al., 2003; Kugler et al., 1980; Newell, 1986), the development of block performance must consider: 1) how organismic constraints can be altered to improve the biomechanical determinants of performance, and 2) the replication of movement dynamics, to promote the self-organisation of competition specific coordinative structures in response to these changing organismic constraints.

Future research should endeavour to identify the exact nature of stress and physiological adaptation occurring at the level of the muscle-tendon unit. Training studies would help identify the effect of different training exercises on the joint kinetic and coordinative strategies when executing the block start, to deeper understand the essential components of a sport specific training exercise.
CHAPTER 6. GENERAL DISCUSSION

6.1 Introduction
Utilising human movement biomechanics and features of dynamical systems theory, this research has examined the training principles of overload and specificity through a biomechanical evaluation of strength training exercises and a competitive motor task: the block start in athletic sprinting. Strength training is often employed in the programmes of elite and developmental athletes (Bolger et al., 2015) and possessing a biomechanical understanding of the competitive task and associated training exercises can assist exercise selection (Irwin et al., 2005; Moir et al., 2018). However, there is a paucity of evidence that has biomechanically examined both the principles of overload and specificity (Dick, 2002; Matveyev, 1981; Siff, & Verkoshansky, 1999) within the theoretical framework of constraints (Newell, 1986), to help practitioners to make informed decisions when prescribing training exercises.

Therefore, the aim of this research was to apply biomechanical analyses and dynamical systems theory to advance understanding of the training principles of overload and specificity within exercise selection. The research purpose was to provide a conceptual framework for evaluating training exercises, to facilitate evidence based decisions when selecting exercises to enhance sports performance.

In order to address the aim of the research, a competitive motor task was required as the vehicle to enhance theoretical and conceptual understanding of exercise selection. The competitive task utilised in the current research was the block start in athletic sprinting. Following a review of literature (Chapter 2), it was established that the block start is critical to success in the 100 m sprint (Willwacher et al., 2016). Furthermore, block performance is founded upon the ability to produce high magnitudes of external force and power (Willwacher et al., 2016), through the generation of extensor moment and power at the lower limb joints (Mero et al., 2006). As a fundamental goal of strength training is to improve the ability of an individual to generate force (Siff, & Verkoshansky, 1999), the block start was deemed an appropriate competitive motor task to address issues surrounding the principles of training and exercise selection.
Through a critical review of training theory literature (Chapter 2), it became clear that possessing an underpinning biomechanical knowledge of the competitive motor task and training exercises is paramount to ensure training is most relevant to the sport (Irwin et al., 2005; Moir et al., 2018; Siff, & Verkoshansky, 1999; Winkelman, 2009). As a result, a two-phase approach was employed to address the overall research aim:

Phase 1. **Technique Analysis: Biomechanics**

Phase 2. **Training Principles: Biomechanics Interface**

In each phase, specific study aims and research questions emerged that were addressed by the investigations outlined in Chapters 3-5, in order to achieve the overall research aim. The development of each research question was an evolving process, with the aims of each study formulated based on the overall thesis aim and the knowledge gained from each preceding study. The key findings from each study and their corresponding research questions are discussed in this chapter, with particular attention to the novel contributions to knowledge and implications for applied practice. Additionally, the appropriateness of the methods used throughout the thesis will be considered and directions for future investigation will be suggested.

### 6.2 Addressing the Research Questions

Chapter 2 highlighted that possessing a biomechanical understanding of a competitive motor task is fundamental to ensuring that training is relevant to performance (Moir et al., 2018; Wild et al., 2011). In addition, expert coaches are known to use their tacit knowledge to develop a mind-set of a skill that influences the selection of training exercises (Irwin et al., 2005). The requirement to understand the biomechanical nature of a competitive motor task, as a basis for exercise selection, formed Phase 1 of the current research.

#### 6.2.1 Phase 1. Technique Analysis: Biomechanics

Previous research seeking to develop a conceptual understanding of block start biomechanics have considered external kinetics (Willwacher, 2016) and lower limb joint kinematics (Bezodis et al., 2015) and kinetics (Mero et al., 2006) in isolation. It was therefore deemed necessary to analyse these characteristics in a holistic manor
in order to understand the biomechanical demand of executing the block start. This formed the bases of the first research question in Phase 1:

**Research Question 1 – What are the external kinetic and lower limb joint kinematic and kinetic characteristics of executing the block start?**

To answer the first research question, a cross sectional analysis of block start biomechanics was undertaken with 17 national and international level male sprinters in Chapter 3. Utilising bespoke instrumented starting blocks and 3D motion analysis permitted the calculation of external kinetic, joint kinematic and joint kinetic data for both blocks / legs during the block start.

The magnitude of external force applied to the front and rear blocks was comparable with previous investigations utilising instrumented starting blocks (Willwacher et al., 2013) and starting blocks mounted to force platforms (Otsuka et al., 2014). A distinct pattern of external horizontal force ($F_Y$) production was identified (Fig. 3.6), with single and double peaked patterns arising for the rear and front block, respectively. In the front block, a latency period in $F_Y$ emerged during the transition between bilateral and unilateral force application (Fig. 3.6). The emergence of this latency may be explained in response to changing task constraints, with an increased demand for the front leg to support body weight during the transition between bilateral and unilateral support. Chapter 3 provided novel information of the continuous nature of horizontal external power generation ($P_Y$), which was found to be opposite to that of total $F_Y$, with a reversed double peak appearance (Fig. 3.6). Understanding the nature of $F_Y$ and $P_Y$ during the block start highlighted the specific role of force application to each block, with the rear being important to initiate horizontal velocity of the centre of mass so that force application to the front block can contribute to the main phase of power generation (Fig. 3.6).

In agreement with previous research investigating the block start (Bezodis et al., 2015; Mero et al., 2006) and early acceleration (Bezodis et al., 2014; Charalambous et al., 2012; Debaere et al., 2013), the ankle joints elicited a dorsiflexion-plantarflexion pattern governed by a plantarflexion moment, resulting in a period of extensor energy absorption followed by generation. The presence of sequential energy absorption and generation was indicative of a stretch shortening action of
the plantarflexors, and was in agreement with other authors (Guissard et al., 1992; Mero et al., 2006).

The front knee joint exhibited extensor moments throughout the majority of block time, but minimal joint motion and thus power generation was observed during the first 40%, before the knee began to extend and generate power. The large magnitude of front knee positive power and extensor work (Table 3.4) confirmed the important energy generating role of the knee joint (albeit the front leg) during the sprint start (Bezodis et al., 2014; Debaere et al., 2013). Delayed power generation of the knee extensors highlighted that the block start also promoted the rotation-extension strategy identified by Jacobs and van Ingen Schenau (1992) as a key feature of accelerative sprinting (Debaere et al., 2013; Moir et al., 2018). The rear knee demonstrated low magnitudes of joint moment and power, and it was theorised that this may reflect a specific role of the rear knee to stabilise the lower limb and facilitate the large forces generated by the hip and ankle being effectively applied to the block.

Both hip joints extended throughout the block phase (Fig. 3.7-3.8) and a major phase of positive extensor power was found at both legs due to dominant extensor moments (Fig. 3.9-3.10). Further computation of relative joint work ($W_{REL}$) highlighted that the rear and front hip joints were responsible for generating 57% and 58% of the total extensor energy generated by the rear and front leg, respectively. This dominant role to generate energy at the hip supports other work that has noted the importance of hip extension during the block phase (Bezodis et al., 2015; Mero et al., 2006; Slawinski, Bonnefoy, Ontanon et al., 2010), and that the specific task demands of initiating motion from a stationary position could shift reliance towards the hip extensors. The calculation of $W_{REL}$ in the block start was novel to the current investigation and provided clear information towards the main generators of lower limb extensor energy. Due to the differing roles of the knee joint, $W_{REL}$ was quantified to be 6% and 27% for the rear and front knee joint, respectively, and 37% and 15%, for the rear and front ankle joint, respectively.

Quantifying external kinetic, joint kinematic and joint kinetic data during the block start soon highlighted that the biomechanical demand was not consistent between the rear and front block / leg, and formed the basis for the second research question in Phase 1:
Research Question 2 – How are the biomechanics of the block start different between the front and rear block/leg?

To answer the second research question in Chapter 3, standardised effect sizes were calculated between front and rear kinematic and kinetic data, with inferences made on the likelihood of the true effect size being at least moderate ($d > 0.6$ or $< -0.6$). Many likely to almost certain differences were observed in kinematic and kinetic variables (Table 3.3, 3.4) and detailed the specific nature as to how the biomechanical demand of executing the block start differed between the front and rear leg.

Results showed that very likely and almost certainly greater magnitudes of peak ($d = 1.41$) and average ($d = 2.54$) vertical force ($F_Z$), respectively, was generated in the front block compared with the rear. However, a likely greater magnitude of peak $F_Y$ was produced in the rear block ($d = -0.86$) (Table 3.3). The between-block differences in $F_Z$ were attributed to the support of bodyweight in the front block during unilateral push, whilst differences in $F_Y$ were thought to be a specific requirement of the rear leg, to apply a large magnitude of $F_Y$ to reduce the time taken to rotate the CM about the front leg (Jacobs, & van Ingen Schenau, 1992).

At the joint level, greater extensor range of motion, and typically higher musculoskeletal demand was observed at the front leg (Table 3.4). At the ankle joint, whilst peak plantarflexion moment was found to be almost certainly greater in the rear block ($d = -1.59$), average extensor moment was not different ($d = -0.01$). The inclusion of both peak and average data was thus warranted to understand the nature of musculoskeletal demand in the block start. Peak and average ankle power and work done during energy generation was meaningfully greater in the front leg (Table 3.4), potentially due to the absence of proximal-distal power generation at the rear leg, decreasing the amount of energy that could be liberated from the knee joint to assist with ankle plantarflexion (Jacobs et al., 1996).

Almost certainly smaller magnitudes of extensor moment, positive power and extensor work were observed at the rear knee joint compared with the front (Table 3.4). These kinetic differences, alongside the different kinematic patterns (Fig. 3.7-3.8), identified that the major source of asymmetry in the block start was at the knee joint. Whilst previous work had quantified knee joint asymmetry in terms of joint
range of motion and angular velocity (Bezodis et al., 2015), a novel finding of the current study was the quantification of between-leg joint kinetic differences. In particular, $W_{REL}$ indicated that whilst the front knee contributed 27% to the total extensor energy generated by the front leg, only 6% was generated by the rear knee joint for the rear leg (Table 3.4).

The musculoskeletal demand to extend the hip joint in the block start was found to be greater in the front leg, with very likely to almost certain ($d = 1.70$ to 5.31) differences found across moment, power and work data (Table 3.4). Although the absolute demand was found to be greater in the front leg, the relative contribution ($W_{REL}$) of the front and rear hip towards total leg extensor energy generation was similar. Overall, $W_{REL}$ indicated that extensor energy generation was predominantly hip and ankle dominant in the rear leg, but more evenly distributed between the knee and ankle in the front leg (Table 3.4). The quantification of $W_{REL}$ enabled novel understanding to the musculoskeletal demand of executing the block start, advancing previous joint kinetic investigations (Mero et al., 2006; Otsuka et al., 2015).

By answering the first two research questions a detailed understanding of the biomechanics of the block start were obtained. However, whilst it is important to possess biomechanical knowledge of the competitive task, it is of further interest for biomechanists, coaches and athletes to understand which variables are related to performance. Based on previous work (Fortier et al., 2005; Otsuka et al., 2014; Willwacher, Herrmann, Heinrich et al., 2013b; Willwacher et al., 2016), it was decided to first address the biomechanical determinants of performance from an external kinetic perspective with the sample of athletes in the current study. This formed the basis of the third research question in Phase 1:

**Research Question 3 – Which external kinetic variables are associated with higher levels of block performance?**

Based on previous work (Bezodis et al., 2010) it was determined that normalised average horizontal power (NAHP) was the best descriptor of block performance. To investigate the relationships between external force production and NAHP, linear bivariate and multiple regression techniques were employed. Pearson correlation coefficients were calculated for all bivariate correlations and magnitude based
inferences were made using 90% confidence intervals and a threshold of 0.1 for the smallest practically important correlation (Batterham & Hopkins, 2006). For the current data sample, r-values of 0.33, 0.50 and 0.66 indicated the thresholds of a likely, very likely and almost certain positive relationship.

Results showed that peak $F_Y$ was found to be very likely (front, $r = 0.57$) and likely (rear, $r = 0.41$) associated with block performance, and highlighted a tendency for peak horizontal force in the front block being of greater importance to successful start performance. This finding disagreed with that of Fortier et al. (2005) who concluded that the magnitude of peak force applied to the rear block was of greater importance to superior block performance. Average $F_Y$ in the front ($r = 0.46$) and rear ($r = 0.44$) block were found to be likely related to NAHP, and these two variables provided the best regression model which explained 86% of the variation in block performance (Table 3.5). Similar standardised regression coefficients and squared part correlations for the front and rear block suggested that neither had significantly greater predictive ability for NAHP (Table 3.5).

Interestingly, a negative correlation between front and rear average $F_Y$ ($r = -0.53$) was observed, highlighting that athletes may have individual preferences for either rear or front block force production, in a similar manner to that observed for the interaction between step length and frequency (Hunter et al., 2004a; Salo et al., 2011). Ultimately, the importance of maximising total (front and rear block) average horizontal force (Otsuka et al., 2014; Willwacher et al., 2016) was confirmed as the key external kinetic determinants of block start performance. Whilst the conclusion of horizontal force production to successful block performance was not novel to the current study, the next step was to explore the lower limb joint kinetic determinants of this external force production, as well as overall block performance. This formed the basis of the next research question in Phase 1:

**Research Question 4 – What are the relationships between lower limb joint kinetics, external kinetics and starting block performance?**

To address this research question, peak and average extensor moment ($M$) and positive extensor power ($P$) at the ankle ($\text{ANK}$), knee ($\text{KNE}$) and hip ($\text{HIP}$) first underwent correlation analysis with average $F_Y$ and NAHP. This approach facilitated a deeper understanding of the lower limb joint kinetic strategies related to the magnitude of
average horizontal force to each block, before extending these relationships to overall block performance.

Almost certain positive relationships with average $F_Y$ were observed for both peak and average rear leg $M_{ANK}$ ($r = 0.71$ and $0.83$, respectively) and $M_{HIP}$ ($r = 0.68$ and $0.80$, respectively). Correlation magnitudes decreased for joint power data, although average $P_{HIP}$ was still almost certainly related to rear average $F_Y$ ($r = 0.73$). Therefore, generating high magnitudes of moment and power at the rear hip early in the rear block phase (Fig. 3.9-3.10), coupled with a large ankle moment to effectively apply these large forces into the rear block, were established as determining characteristics of the magnitude of average $F_Y$ generated in the rear block. In the front block, there were many meaningful positive relationships between average $F_Y$ and moment data across all joints, although relationship strength increased in a proximal-distal manor (Fig. 3.12). However, peak and average power at the knee joint possessed the strongest relationships with average $F_Y$ ($r = 0.56$ and $0.57$, very likely, respectively). Thus, although the ability to generate large moments across all lower limb joints at the front leg were associated with $F_Y$, it was the ability to organise powerful extension of the knee joint that was critical to the magnitude of horizontal force applied to the front block (Fig. 3.12).

The next step was to investigate which lower limb joint kinetic relationships extended to overall starting block performance (NAHP). This was exploratory in nature because it was already established that there were clearly different individual strategies with respect to front and rear $F_Y$ but together explained $86\%$ of the variation in NAHP (Table 3.5). The strongest and only very likely relationship with NAHP was found for front peak $P_{KNE}$ ($r = 0.55$). Several other likely relationships were observed across front leg joint kinetic variables and were all within a small range of r-values ($r = 0.35$ to $0.46$), and only two meaningful relationships were found at the rear leg (peak and average $M_{ANK}$).

All variables possessing at least a likely relationship with NAHP were then input into a stepwise multiple regression, to elucidate the key joint kinetic determinants of block performance. The best regression model explained $60\%$ of the total variance in NAHP and consisted of three variables: rear average $M_{ANK}$, front average $M_{HIP}$ and front peak $P_{KNE}$. The main strategies required for successful block start performance were thus identified and could be explained. Front hip moments are
large and extensor for approximately 80% of the block phase (Fig. 3.9) and thus can have a considerable opportunity to influence block performance, whilst the main phase of positive extensor knee power in the front leg (Fig. 3.10) coincides temporally with peak external power (Fig. 3.6). High extensor moments at the rear ankle may reflect a neuromuscular characteristic of superior block performers to ensure resistance to dorsiflexion, facilitating horizontal orientation of large forces generated in minimal time (Cavagna, 1977; Guissard et al., 1992; Rabita et al., 2015).

Quantifying the key lower limb joint kinetic variables related to the magnitude of horizontal force applied to each block, and those able to explain 60% of the variation in block performance was a unique finding of the current study and provided a novel contribution to knowledge of sprint biomechanics. However, a remaining 40% of unexplained variance, coupled with the observation of a specific organisation of joint kinematics and kinetics (Fig. 3.7-3.10), implied that there was still more to understand about the organisation of movement in the block start. Furthermore, Chapter 2 alluded to the importance of understanding sports performance from a dynamical systems perspective (Davids et al., 2003; Glazier, 2015; Newell, 1986), quantifying intra-limb joint coordination and its variability to discern the organisation of movement to execute a particular task (Turvey, 1990). In addition, previous research has suggested that comparing movement patterns between training and competitive tasks might be better addressed from a coordinative perspective (Irwin & Kerwin, 2007a; Romanazzi et al., 2015; Wilson et al., 2009). Based on the findings of Chapter 3 and previous work, Chapter 4 continued Phase 1 of the research and formed the next research question:

**Research Question 5 – What are the patterns of intra-limb joint coordination and coordination variability when executing the block start?**

In order to answer this question, intra-limb, inter-joint coordination was quantified by applying modified vector coding (Chang et al., 2008; Hamill et al., 2000; Needham et al., 2014) to angle-angle plots of the hip-knee (H-K), hip-ankle (H-A) and knee-ankle (K-A) joint couples to obtain coupling angle (CA) data. The resulting group average CA and intra-athlete coupling angle variability (CAV) was presented throughout the rear and front leg phases so that the nature of joint coordination and variability could be established. CA data were classified into eight coordination
patterns (Chang et al., 2008) to categorise the emergent coordinative patterns during execution of the block start.

Front leg coordination patterns supported previous work showing that to maximise forwards propulsion, a specific strategy is required that delays extension of the more distal joints until their contribution can maximise forwards translation of the centre of mass (Jacobs & Van Ingen Schenau, 1992; Moir et al., 2018; Bezodis et al., 2015) (Fig. 4.5). This strategy was highlighted by proximal extension coordination preceding in-phase extension coordination patterns, with the onset of an in-phase pattern occurring between 60-80% of block time (Fig. 4.5). The emergence of proximal and in-phase extension coordination patterns coincided with periods of lowest variability, and were consistent across all athletes through individual analysis of coordination patterns (Fig. 4.8). From a dynamical systems perspective, these coordination patterns could thus be considered task-specific coordinative structures (Kugler et al., 1980) that emerged through self-organisation in response to imposed constraints on action (Newell, 1986), that should be considered when assessing the movement specificity of training exercises (Irwin & Kerwin, 2005; Romanazzi et al., 2015; Wilson et al., 2009).

In continuation of Chapter 3, inter-limb asymmetry was shown to be most prominent in coordination patterns for joint couples encompassing the knee joint (Fig. 4.4-4.5), providing a novel perspective to support previous analyses of single joint kinematics (Bezodis et al., 2015) and kinetics (Mero et al., 2006) during the block phase. For the H-A joint couple, the front leg demonstrated a larger frequency (54%) of proximal extension coordination compared with the rear leg (16%) and indicated a faster transition between ankle dorsiflexion and plantarflexion (Fig. 4.5). The faster transition observed at the rear leg was theorised to be a result of time constraints imposed on the rear ankle joint to contribute towards horizontal motion of the athlete (Debaere et al., 2015).

For all joint couples, CAV profiles showed highest variability at the onset of movement, followed by secondary local maxima surrounding the reversal of joint motions (Fig. 4.4-4.5). Increases in coordination variability can be indicative of impending state changes (Haken et al., 1985; Heiderscheit, 2000), which appeared to be supported by the current study. As the onset of movement could be considered to be the greatest change in state, the larger variability associated with this phase
could be a result of increased physical demand (Wilson et al., 2016) and the need for flexibility during this state change so that task-specific coordinative structures can be self-organised in the context of changing constraints (Newell, 1986).

Following the quantification of intra-limb joint coordination and variability during the block start, it was of further interest to investigate whether these features of movement dynamics could explain differences in performance level. This formed the bases for the next two research questions addressed in Chapter 4:

**Research Question 6 – How are the coordination patterns observed when executing the block start affected by the level of performer?**

To address this research question, individual profiles of coordination patterns were examined using colour maps and qualitative data visualisation techniques (Fig. 4.7-4.8). Across all joint couples, only front leg K-A coordination demonstrated a performance related trend (Fig. 4.7-4.8). Results showed that the top eight performers appeared to demonstrate a greater frequency of distal extension coordination during the first 40% of movement time. Potentially, this coordinative feature indicated a technique of superior block performers to maintain stability through the front knee joint to transfer large forces generated by the hip, and delay knee extension until later in the block start movement (Jacobs & van Ingen Schenau, 1992). Previous research has been able to establish other kinematic variables associated with superior performance, such as hip extension angular velocity (Bezodis et al., 2015) and joint angles during the set position (Mero et al., 1983; Slawinski, Bonnefoy, Leveque et al., 2010). The current study has added extra depth to these kinematic analyses to understand the techniques adopted by superior block performers, providing novel insight towards the specific coordination patterns in those athletes able to achieve greater magnitudes of NAHP.

Individual analyses reinforced group level findings that proximal extension and in-phase extension joint coordination patterns were task specific coordinative structures as these patterns emerged in all athletes (Fig. 4.7). These coordination patterns emerged following a period of high between-athlete variation in coordination pattern, which may be reflected by the rather homogenous sample of athletes in terms of sprinting expertise (all were within 85-95% of the 100 m world record). Thus, although performance level differed across the group, all athletes had
learned the coordination patterns required to manage the specific task constraints of the block start. Initial inter-athlete variation in joint coordination may have reflected the management of individual organismic and environmental constraints, so that consistent patterns of coordination could be achieved during the task (Newell, 1986).

Research Question 7 – How is coordination variability influenced by the level of performer?

To explore the potential relationships between coordination variability and block performance, quadratic regression analyses was performed between discrete measures of coordination variability and NAHP. Two discrete measures of joint coordination variability were quantified: the average value of CAV across the entire normalised phase duration (CAV) and the average value of CAV across the first 20% of the normalised phase duration (CAV20) for each leg. The rationale for calculating CAV20 emerged from the preceding results, which highlighted that this region exhibited the highest magnitude of variability (Fig. 4.4-4.5). Quadratic regression analysis was undertaken based on previous evidence that the relationship between coordination variability and task expertise has demonstrated quadratic features (e.g. Wilson et al., 2008).

Only one significant quadratic regression model was established, amidst many positive (U-shaped) and negative (inverted U) regression models that were not significant and possessed R² values of < 0.2 (Fig. 4.9-4.10). The significant relationship was observed for the front leg H-A joint couple (R² = 0.487, P < 0.05), but possessed linear features (R² = 0.445, P < 0.05) and explained a reduction in coordination variability as block performance increased. Similar findings were shown in race walking athletes, with international athletes eliciting lower coordination variability than their national level counterparts (Cazzola et al., 2016), and these results support the idea that successful task performance may require a smaller, functional level of coordination variability (Glazier & Davids, 2009; Robins et al., 2008). However, the inconsistent and many not significant relationships provided little clarity to coordination variability being influenced by performance level. An explanation for the current results could be linked to the rather homogenous sample with respect to task ‘expertise’. All athletes may thus have been exploiting the inherent variability of their biological motor system in a functional
manor, in order to adapt to subtle changes in constraints between trials to maintain task specific coordinative structures (Bartlett et al., 2007; Davids et al., 2003; Glazier & Davids, 2009; Hamill, 1999; Kelso, 1995).

6.2.2 Phase 1 Summary
Throughout Phase 1 of the current research, a competitive motor task, the block start in athletic sprinting, was investigated in detail utilising conventional biomechanics (Chapter 3, Research Questions 1-3) and dynamical systems approaches (Chapter 4, Research Questions 4-7). In both Chapters 3 and 4, research aims centred on biomechanical understanding of the competitive motor task and those techniques associated with superior performance. By answering Research Questions 1-7, an underpinning biomechanical knowledge of the competitive motor task was established and could be used to examine the principles of training in a range of exercises, to help develop current practice within exercise selection.

6.2.3 Emergence of Analysis Themes
The principles of training suggest that a training exercise aimed at improving sports performance should overload relevant characteristics of the sports skill, in a specific manor so that musculoskeletal adaptation can positively impact subsequent performance (Matveyev, 1981; Siff, & Verkoshansky, 1999; Verkoshansky, 2011). Ensuring the transfer of increased neuromuscular potential to enhanced sports performance is considered to be governed by similarity in movement pattern between the competitive and training tasks (Wild et al., 2011; Wilson et al., 1996; Young, 2006). From a constraints based approach (Newell, 1986), movement self-organises through interaction amongst imposed constraints on the system, and is often viewed as the coordination of functionally linked segments or joints (Glazier, 2015; Hamill et al., 1999).

Through consideration of these concepts in Chapter 2, alongside the findings of Chapters 3 and 4, it was prominent that two consistent themes emerged that can dictate the efficacy of a training exercise to improve sports performance. Firstly, understanding joint-level musculoskeletal demand through single joint kinematics and kinetics can inform the magnitude and nature of imposed stress on the system that can lead to musculoskeletal adaptation (Selye, 1936, 1951). Secondly, understanding the self-organisation of intra-limb joint coordination and variability
provides knowledge of the *movement dynamics* associated with executing a competitive task, influencing the task specific utilisation of musculoskeletal changes (organismic constraints) to enhance sports performance. These two themes established a conceptual framework for comparing a training exercise with a sports skill, which formed Phase 2 of the research.

6.2.4 Phase 2. Training Principles: Biomechanics Interface

To examine the principles of overload and specificity within exercise selection, a range of training exercises were required to compare characteristics of musculoskeletal demand and movement dynamics with the competitive motor task (block start). Training exercises are often placed on a spectrum from general (not specific) to specific based on a unidimensional approach of maximising similarity with the competitive skill (Crick, 2009; Burnie et al., 2017; Moir et al., 2018; Wild et al., 2011; Young et al., 2001). Therefore, the current study sampled a range of exercises across this spectrum, to facilitate a reconceptualisation of what constitutes a ‘sport specific’ training exercise, based on both overload and specificity principles of training (Matveyev, 1981; Siff, & Verkoshansky, 1999), the theoretical framework of constraints (Newell, 1986), and biomechanical determinants of performance.

In total, seven training exercises were selected that possessed relevance to strength training practices within sprinting, that were currently being used with the current sample of athletes across their periodised training cycle. Exercises included a near maximal concentric only back squat (BS$_{90}$), a heavy (JS$_{60}$) and light (JS$_{0}$) loaded concentric only jump squat, and two horizontally projected ballistic jumps (HJ and MBD). For each horizontal jump exercise, two variations in foot positioning were investigated: traditional bilateral stance (HJ$_{BL}$ and MBD$_{BL}$) and a split stance (HJ$_{SP}$ and MBD$_{SP}$). The rationale for including these variations was to explore the effect of manipulating task constraints to enhance perceived replication of the competitive motor task, on the underlying biomechanical features of overload and specificity.

Based on the two analysis themes, *musculoskeletal demand* and *movement dynamics*, Research Questions 8 and 9 were formed that would help inform objectivity within exercise selection and contribute to advancing theoretical understanding of the principles of training.
Research Question 8 – How do lower limb joint kinematics and kinetics compare between the block start and traditionally viewed general and specific training exercises?

To compare single joint kinematics and kinetics between training exercises and the block start, both discrete and continuous methods were utilised. Discrete magnitudes of peak and average extensor joint moment and power generation were compared using standardised effect sizes (Cohens $d$) and magnitude-based inferences (MBI) (Batterham & Hopkins, 2006). As with Chapter 3, the threshold of smallest meaningful difference was set at $d = 0.6$, reflecting a ‘moderate’ effect size difference and a more conservative approach than using a ‘small’ effect ($d = 0.2$). In addition to discrete measures, joint angle, moment and power data underwent continuous analysis so that magnitudes of difference ($d$) could be inspected across the normalised waveform and the locality of differences could be visualised (Manal & Stanhope, 2004).

In comparison with the competitive motor task (block start), aside from BS$_{90}$, all other exercises were capable of eliciting greater musculoskeletal demand at the ankle joint, with plantarflexion moment and power generation being meaningfully greater across many of the investigated exercises (Table. 5.4). However, the exercise possessing the largest magnitude of difference with the block start was dependant on the variable of interest. The observed larger plantarflexor moments that contributed to increased power generation, could be explained by the increases in ankle dorsiflexion during each exercise (Fig. 5.2), shifting the plantarflexor musculature towards more favourable force-length state (Anderson et al., 2007; Hahn, et al., 2011; Sale et al., 1982). Whilst many exercises were shown to provide an overload stimulus to facilitate physiological adaptations in the capacity of the ankle plantarflexors to generate moment and power (Matveyev, 1981; Siff, & Verkoshansky, 1999), the nature of the overload stimulus lacked correspondence with the competitive task with respect to joint angles. Thus, the efficacy of any adaptations to be utilised within the constraints of the competitive skill might be threatened by the differences in ankle joint angle (Morrissey et al., 1995; Rhea et al., 2016). The importance of elucidating the bandwidth of joint angle specific adaptations during dynamic training tasks was highlighted as an important avenue for future research.
At the knee joint, key findings highlighted the meaningful greater magnitude of front leg average $M_{KNE}$ elicited during the loaded squat exercises ($JS_{60}$, $BS_{90}$) compared to the block start (Table 5.4). For all horizontal jump exercises, negative differences or no differences were observed (Table 5.4), identifying the absence of global musculoskeletal overload during these exercises to generate extensor moments at the knee joint. Continuous analysis (Fig. 5.6) revealed that the largest overload in knee extensor moments occurred at the beginning of movement, when joint angles between the block start and all squat variations were similar (Fig. 5.5). Thus, $BS_{90}$, $JS_0$ and $JS_{60}$ were considered effective exercises for specifically overloading the extensor moment demand of executing the block start at the front knee joint (Irwin et al., 2007; Siff, & Verkoshansky, 1999), with increasing external load being a strategy to maximise overload (Fig. 5.6). These data provided mechanical explanation for maximal squat strength being related to sprint performance (Seitz et al., 2014) and justified the use of near maximal loads being implemented into the overall training programme of elite sprinters (Moir et al., 2018). Whilst no positive and meaningful differences existed in discrete variables for the horizontal jump exercises, continuous analysis identified local overload during these exercises also at the beginning of movement (Fig. 5.5).

Only when considering individual effect sizes were positive and meaningful differences established for front $P_{KNE}$, which were distributed across several exercises (Table 5.5). The exercise exhibiting the largest effect size was individual dependent, supporting the emergence of individual biomechanical strategies when performing the same task (Bradshaw et al., 2007; Dufek & Bates, 1990), and the importance of considering individual biomechanical strategies for determining optimal training practices (Marian et al., 2016; Morin & Samozino, 2016; Sarabia et al., 2017). Acknowledging the individual nature of musculoskeletal overload was therefore identified as a factor to be incorporated into an evidence based exercise selection framework.

Hip extensor moments also showed large to extremely large positive differences across all exercises at the onset of movement (Fig. 5.9), during which similarity in hip joint angle was observed (Fig. 5.8). The greatest discrete differences in $M_{HIP}$ were observed for $BS_{90}$ (Table 5.4), suggesting that this exercise could be most effective at stimulating functional adaptations in hip extensor strength (Matveyev, 1981). Furthermore, as front leg average $M_{HIP}$ was one of the key determinants of
block performance, BS\textsubscript{90} could be considered to elicit specific musculoskeletal overload to the biomechanical determinants of performance. The efficacy of BS\textsubscript{90} to facilitate competition task specific increases in hip and knee extensor moments, brought into question current approaches that would consider BS\textsubscript{90} as a non-specific training method for sprint running (Crick, 2009; Wild et al., 2011; Young et al., 2001).

Whilst BS\textsubscript{90} was shown to elicit the greatest overload in hip extensor moments, all exercises showed large to extremely large differences at the beginning of movement (Fig. 5.9). The importance of continuous analysis as well as quantifying joint level overload was therefore recognised, and suggested that similar local overload could be achieved under a range of imposed task constraints (Newell, 1986), such as near maximal external loads (BS\textsubscript{90}) or a preceding countermovement (HJ). Whilst most exercises were capable of providing overload with respect to hip extensor moment, no exercise was able to overload or even replicate the hip extensor power generating characteristics of the block start (Table 5.4, Fig. 5.910). Whilst adaptations in hip extensor power could be realised as a consequence of increasing strength (Cormie et al., 2011a; Newton & Kraemer, 1994), more research is required to identify those exercises capable of overloading the magnitude of hip extensor power exhibited during the block start.

Answering Research Question 8 exposed the complexity within exercise selection with respect to ensuring competition task specific musculoskeletal overload, as all exercises were found to elicit aspects of joint kinetic overload across both discrete and continuous analyses (Table 5.4, Fig. 5.1-5.9). Support was thus provided towards a mixed model approach by which a variety of exercises should be used to develop the neuromuscular potential of an athlete (Cormie et al., 2011b). Within this approach, the current study would suggest that with respect to musculoskeletal overload, the most appropriate exercise would be influenced by the biomechanical determinant of performance of interest, in addition to the individual athlete.

**Research Question 9 – How does intra-limb joint coordination and coordination variability compare between the block start and traditionally viewed general and specific training exercises?**

To answer this research question, both discrete and continuous analyses were again conducted so that a comprehensive picture of movement similarity between
each training exercise and the block start could be achieved. To compare intra-limb joint coordination patterns, modified vector coding was used to produce coupling angle (CA) profiles across the normalised time cycle, that were classified using a binning approach (Chang et al., 2008). Colour coding the differences coordination patterns (bins) for each instance across the normalised time cycle formed the analysis of continuous data (Fig. 5.11-5.13). To accompany the continuous analysis, a discrete measure of difference in coordination patterns across the entire movement was also computed (CA\textsubscript{DIF}) (Table 5.6).

Increased similarity in coordination patterns between the training exercises and block start were found for joint couples at the front leg compared with the rear, caused by the emergence of rear leg anti-phase coordination in the block start towards the end of movement (Fig. 5.11, 5.13). Quantifying overall differences in joint coordination using CA\textsubscript{DIF} (Table 5.6) demonstrated that JS\textsubscript{0}, JS\textsubscript{60} and BS\textsubscript{90} were often able to closer replicate the emergent coordination patterns during the block start. Continuous analyses provided further insight towards the similarity in joint coordination profiles between each exercise and the block start (Fig. 5.11-5.13). At the front leg, all exercises settled into similar coordination patterns to the block start after approximately 50% of movement time, when in-phase extension coordination began to emerge. Therefore, with respect to the replication of competition task specific coordinative structures presented in Chapter 4, all exercises could be considered specific to the nature of the block start (Irwin & Kerwin, 2007a; Romanazzi et al., 2015).

Low inter-exercise variation in the replication of in-phase extension coordination patterns, in addition to discrete CA\textsubscript{DIF} scores, questioned current practice of determining the ‘specificity’ of an exercise based on the appearance of replicating competition task movement patterns (Crick, 2009; Wild et al., 2011). Furthermore, manipulating task constraints to a split stance during the HJ and MBD exercise in order to closer resemble the postures of the block start, increased coordination similarity for the rear leg, but decreased coordination similarity for the front leg (Table 5.6). The current study therefore encouraged the use of intra-limb joint coordination analysis within strength and conditioning, to provide a deeper understanding of movement similarity between a competitive and training task (Irwin & Kerwin, 2007a; Romanazzi et al., 2015; Wilson et al., 2009). The current research demonstrated progression beyond visual assessment of postures (Wild et al., Young
et al., 2001) or single joint kinematics (Okkonen & Hakkinen, 2014), to determine movement pattern specificity.

At both the front and rear leg, intra-limb joint coordination patterns showed the greatest inter-exercise differences at the onset of movement (Fig. 5.10-5.12). The different task constraints for each exercise with respect to starting postures and intended direction of centre of mass projection (Newell, 1986), as well as differences in the changing state of the system at movement onset (Heiderscheit, 2000), likely explained the early differences in joint coordination. The identification of local differences in joint coordination was a strength of the current research, and can be indicative of potential subtle changes in response to training (Leirdal & Ettema, 2008). For example, the emergence of front leg in-phase flexion K-A joint coordination at the onset of movement during the horizontal jump exercises (Fig. 5.12), may promote conflicting features of successful task execution, as distal flexion joint coordination was identified as a characteristic of superior block start performance (Chapter 4).

Coaches often perceive that the time taken to realise neuromuscular adaptations (changing organismic constraints) in the competitive motor task is dependent on the similarity in movement coordination (Burnie et al., 2017). Whilst the current study did not assess inter-muscular coordination, which should be a topic of future research, investigating intra-limb joint coordination has provided valuable insight into the organisation of multiple degrees of freedom into emergent coordination patterns (Bernstein, 1967; Kugler et al., 1980; Newell, 1986). With respect to developing training theory, understanding similarity in joint coordination may explain how an exercise can promote competition task coordination patterns that may reduce the time taken for altered organismic constraints (increases in neuromuscular strength and power) to improve competitive motor task performance.

In conjunction with examining patterns of joint coordination, it was important to evaluate the magnitude of coordination variability in the analysis of movement dynamics (Irwin & Kerwin, 2007a), to understand how each exercise may encourage the ability to maintain task outcome by promoting adaptable performers that can self-organise task specific coordinative structures in response to changing constraints on action. To provide a comparison of joint coordination variability between the block start and each training exercise, measures of variability across
the entire movement (CA\textsubscript{V}) and first 20\% of movement (CA\textsubscript{V20}) were compared using standardised effect sizes (d) and MBI, given the non-circular nature of CAV (Hamill, 1999).

Both measures of variability were generally higher in JS\textsubscript{0}, JS\textsubscript{60} and BS\textsubscript{90} compared with the block start, whereas similar magnitudes of CA\textsubscript{V} and CA\textsubscript{V20} were found between the block start and horizontal jump exercises (Table. 5.8). The increased CA\textsubscript{V20} in the squat type exercise was contrary to expectations, given the controlled starting position in comparison to the self-selected depth of the horizontally projected jump exercises (Table 5.2). However, the observed finding was theorised to be a result of: 1) the specific task constraint during the horizontal jumps to manage propulsive (horizontal) and supportive (vertical) external forces, reducing the number of available solutions (degrees of freedom) to achieve the task outcome (Newell, 1986); 2) a more pronounced state change in JS\textsubscript{0}, JS\textsubscript{60} and BS\textsubscript{90} due to the lack of preliminary countermovement (Ghez & Sainburg, 1995; Heiderscheit, 2000; Wilson et al., 2016); and 3) the interaction between barbell and athlete managing optimal positioning of the external load in relation to the base of support.

The lack of meaningful differences in CA\textsubscript{V} and CA\textsubscript{V20} during the horizontally projected exercises (Table 5.8) would suggest that these exercises were able to promote similar magnitudes of joint coordination variability as elicited in the block start, and would thus be considered specific to the self-organising nature of the competitive movement (Irwin & Kerwin, 2007a). As Chapter 4 established that the magnitude of joint coordination variability was not associated with performance level, the increased variability emerging from the squat type exercises could be interpreted as potentially harmful to performance. Conversely, facilitating a wider landscape of solutions to initiate movement but subsequently settle on consistent coordinative patterns that are functionally linked to task performance (in-phase extension), could be deemed encouraging features of the squat type exercises for promoting flexible and adaptable performers (Glazier, 2015; Glazier, & Davids, 2009; Hamill et al., 1999; Holt et al., 1995; Kelso, 1995).

Answering Research Question 9 extended the analysis of single joint kinematics and kinetics to enhance underlying knowledge of the concept of movement specificity, and how a training exercise may influence the transfer of training (Bondarchuck, 2007; McBride et al., 2002; Wilson et al., 1996; Young., 2006).
Contention for classifying exercises without knowledge of intra-limb coordination surfaced from the current research, with traditionally viewed less specific (e.g. BS\textsubscript{90}) and more specific (HJ and MBD variations) exercises both encouraging coordinative structures linked to competitive motor task outcome.

**6.3 Appraisal of Methodology**

6.3.1 Study Design

Throughout the current research, national and international level male sprinters were representatively sampled and utilised within a cross sectional study design to address the overall research aim and specific research questions in each phase. A cross sectional design enabled a biomechanical technique analysis of the block start to be undertaken (Chapter 3 and 4), key characteristics associated with superior performance to be established (Chapter 3 and 4), and a biomechanical evaluation of training exercises to be performed in order to advance knowledge of the principles of training within exercise selection (Chapter 5).

For the purpose of this research, a cross-sectional design was justified. However, cross sectional designs only provide an observation of biomechanical variables at a single time point. As the participants of this study were experienced sprinters, the biomechanical data collected was likely reflective of their natural technique. However, it is recognised that even in elite athletes, technique can vary between training sessions (Bartlett et al., 2007), which should be considered by the reader when extrapolating the results of the current research. To help overcome the surrounding issues of intra-athlete variation in technique, multiple trials (six) were utilised consistently throughout this research. This number of trials is twice that recommended as a compromise between statistical issues and practicality (Mullineaux, et al., 2001), and helped provide a more representative account of each athlete’s natural technique (Mullineaux, 2008).

A combination of group and single-subject (Bates, 1996; Dufek & Bates, 1990) research designs were embraced in the current thesis. This allowed the current research to consider the individual uniqueness in biomechanical techniques to achieve the same task (Bradshaw et al., 2007), alongside group trends that enhance the generalisation to the wider population. The integration of group and single-
subject research designs was intended to be complimentary, to provide the reader with more detail to make their inferences. Combining these research designs supported the emergence of key proximal and in-phase extension coordination patterns at the front leg during the block start (Chapter 4), in addition to highlighting coordinative patterns demonstrated by superior performers (Chapter 4). Furthermore, the addition of within-athlete analysis in Chapter 5 highlighted the individual nature of musculoskeletal overload, especially with respect to front knee joint extensor power generation.

6.3.2 Data Collection
In order to analyse the biomechanics of block start technique, multiple data collection methods were utilised to obtain the necessary information to quantify external force, joint kinematic, joint kinetic, intra-limb coordination and coordination variability data. In recent years’, automated 3D motion analysis systems have emerged as the preferred method for the measurement of kinematics within sports biomechanics research (Milner, 2008), enabling high sampling frequencies (250 Hz) with minimal processing demand compared with video analysis. A limitation of these systems is the more invasive nature compared with video analysis due to the fixing of markers to the athletes skin. To minimise the marker-athlete interference with technique, all participants completed their warm up with markers attached, and medial markers were removed following static calibrations.

To collect external force data during the block start, customised instrumented starting blocks were used (Willwacher, Feldker, Zohren et al., 2013). These starting blocks have successfully measured starting block forces in over 150 athletes including the fastest athlete in history (Willwacher et al., 2016) and facilitated seamless collection of starting block forces for the 17 male sprinters in the current study. Precautions were made to ensure valid collection of block forces, including mounting them onto an industry standard track surface (Mondo, UK) and ensuring that athlete’s feet were solely in contact with the blocks during the push phase.

A methodological issue arose through using the instrumented starting block system with respect to estimating the centre of pressure (COP) to be used within the inverse dynamics calculation of resultant joint moments (Chapter 3). The computed COP from the instrumented starting blocks contained error, likely resulting from the point of force application being outside of the location of the load cells (Fig. 3.4). Whilst
previous research to quantify joint kinetic data in the block start assigned the COP to the location of the MTP joint centre (Mero et al., 2006), the static nature of this method was improved upon by creating a virtual projection of the MTP joint centre onto the starting blocks (Fig. 3.5). The result was a centre of pressure estimate that was able to move along the block surface based on individual athlete foot motion, and was deemed the best available method for estimating the COP for inverse dynamics calculations. The chosen method was also justified due to issues with converting the COP from the instrumented starting blocks into the global coordinate system. Factors such as determining the exact location of the load cells in the global coordinate system and movement of the blocks between trials affected the accuracy and reliability of converting COP from local to global coordinates.

The different COP calculations between the block start and training exercises may have implications for the comparison of musculoskeletal demand in Chapter 5. However, it should be recognised that the best available method of COP estimation was utilised in each instance and the reader is encouraged to consider the wider application of this research: to provide a framework for understanding the theoretical underpinning of exercise selection, based on a multidimensional approach to overload and specificity training principles.

6.3.3 Data Analysis

Whilst three-dimensional kinematics were collected in the current study, only x-axis (flexion-extension) mechanics were considered. This is in alignment with previous research in sprint acceleration (Bezodis et al., 2008; Bezodis et al., 2014; Bradshaw et al., 2007; Charalambous et al., 2012; Johnson & Buckley, 2001; Mero et al., 2006). However, other studies have shown the contribution of abduction-adduction and internal-external rotation to lower limb joint motion in the block start (Slawinski, Bonnefoy, Ontanon et al., 2010) and squat exercises (Swinton, Lloyd et al., 2012). Whilst considering the 3D nature of movement organisation provides an avenue for future work to build upon the current research, the primary focus of the current research was to provide a detailed account of musculoskeletal demand and movement dynamics associated with leg extension.

Previous research has acknowledged the contribution of hand forces (Graham-Smith et al., 2014) and upper body and trunk motion (Slawinski, Bonnefoy, Ontanon et al., 2010; Slawinski et al., 2017) to overall motion of the centre of mass in the
block start. Although upper body joints were not included in the present study, it would be of interest in future work to investigate whether including joint kinetics of the upper body could help to explain more of the variation in starting block performance that was established in Chapter 3.

6.3.3.1 Measurement of Coordination & Coordination Variability

In the current research, a modified vector coding technique (Chang et al., 2008; Needham et al., 2014) was employed to quantify intra-limb, inter-joint coordination and subsequent coordination variability. Vector coding provides an easily interpretable method for assessing movement coordination (Chang et al., 2008; Tepavac & Field-Fote, 2001; Heiderscheit et al., 2002; Needham et al., 2014) as the coupling angle can be intuitively related back to joint angular motion. Another popular measure of movement coordination is continuous relative phase (CRP) (Kelso, 1995; Hamill et al., 2000), which provides a higher order analysis of phase differences based on the angular position and velocity of two oscillators. Whilst including temporal information in CRP may afford advantages over vector coding by increasing sensitivity, methodological issues surrounding normalisation, the assumption of sinusoidal motion, and interpretation to conceptual understanding of joint motion are inherent to CRP analysis (Wheat & Glazier, 2005; van Emmerik et al., 2014).

Ultimately, the methodological choice should be based on the specific research question (Hamill et al., 2000; Wheat & Glazier, 2005). In the current research, it was of interest to investigate the relative motion of functionally linked joints of the lower limb between tasks that naturally possess differences in angular velocity of the joints (e.g. BS$_{90}$ vs. HJ$_{BL}$). Thus, selecting a method independent of joint angular velocity was required to understand the nature of intra-limb joint coordination between motor tasks. A limitation of vector coding relevant to the current study could be the artificial increases in variability when consecutive data points are in close proximity, for example during the onset of movement or joint reversals when there is minimal joint displacement (Heiderscheit et al., 2002). This should therefore be acknowledged when interpreting the CA$_V$ and CA$_{V20}$ data in Chapter 5 alongside the offered mechanical explanations.
6.3.3.2 Statistical Analysis

Throughout the current research, magnitude-based inferences were employed when investigating between-group mean differences (Batterham & Hopkins, 2006). This approach provides a practical alternative to traditional null-hypothesis testing and statistical significance at a $P$-value of 0.05, which has often been stated as overly conservative in studies of elite athletes with small sample sizes (Hopkins, 2009; Mengersen et al., 2016). Instead of intending to prove or disprove that there is no effect, MBI understands that there are seldom truly zero effects in nature and it is more important to estimate the true magnitude of an effect (Hopkins et al., 2009).

The importance of including effect size statistics has been recognised as a more important goal of statistical inference (Wilkinson, 2014; Batterham & Hopkins, 2006; Hopkins, 2009), and MBI provides a framework by which the likely true value of this effect size can be interpreted practically, to make meaningful inferences about the difference between two means. Although MBI has received criticism, surrounding issues of not being a Bayesian approach and the subjective thresholds used during interpretation (Welsh & Knight, 2015), other statisticians have promoted MBI as a practical solution for combining frequentist approaches with elements of Bayesian thinking, by estimating the magnitude of population effects with reference to a priori estimate of practical worthwhile magnitudes (Wilkinson, 2014).

Further criticism of MBI statistics has also been that it is not conservative enough to prevent against Type 1 error (finding an effect that is not there) (Welsh & Knight, 2015). In recognition of this potential limitation, a smallest meaningful difference threshold was set at $d = 0.6$ in the current research. This represents a ‘moderate’ effect and is more conservative than the ‘small’ ($d = 0.2$) threshold often suggested (Batterham & Hopkins, 2006). In addition, throughout the current research, where MBI has been used, raw effect sizes ($d$) and 90% confidence intervals (CI) have been provided to the reader. Ultimately, MBI affords greater interpretation of statistical tests that allows the scientist to interpret the true magnitude of an observed effect, instead of accepting or rejecting the null hypothesis based on $P < 0.05$. Utilising MBI, the current research was able to provide objective but applied means to understand differences between limbs (Chapter 3), and between training exercises and the block start (Chapter 5).
Given the circular nature of coupling angle data, an alternative method was required to analyse group mean differences in intra-limb joint coordination between the block start and each training exercise (Chapter 5). Previous research has rarely conducted quantitative comparisons of vector coding data and inferences are usually made qualitatively by profiling coordination across the normalised time cycle (Needham et al., 2014). Whilst the ‘binning’ approach presented by Chang et al. (2008) has allowed comparison of the duration spent in each coordination pattern, a need to determine quantitative comparisons of coupling angle between groups or conditions has been recently recognised (Freedman-Silvernail et al., 2008). In the current study, a measure of overall difference in coordination profiles between two tasks ($\text{CA}_{\text{DIF}}$) was computed by expressing the summed difference between coordination patterns for each instance across the normalised time cycle as a percentage (Chapter 5, section 5.2.4). Thus, a $\text{CA}_{\text{DIF}}$ score of 0% would indicate that for each point across the normalised time cycle, the coordination pattern for the two conditions was within the same classification. Whilst unique to the current study to explore differences in movement coordination, binning approaches have been advocated to compare between-group difference in CA data (Freedman-Silvernail et al., 2018). Thus, $\text{CA}_{\text{DIF}}$ could provide a practical alternative to directional statistics to compare circular data between groups.

A strength of the current research was the complimentary nature of discrete and continuous analysis methods. The addition of continuous analysis of joint kinetic and coordination data through colour maps (Chapter 5), aided the visualisation of local overload and specificity characteristics of each exercise. Utilising both discrete and continuous approaches has provided a practical method that can be used within applied strength and conditioning practice, enabling coaches to easily interpret similarity and difference between a competitive motor task and training exercise.

### 6.4 Novel Contributions to Knowledge & Practical Implications

The current research has provided novel contributions to both conceptual understanding of the block start in athletic sprinting, and the interface between biomechanics, training theory (Matveyev, 1981; Siff, & Verkoshansky, 1999) and the theoretical model of constraints on action (Newell, 1986). Emerging from the current research are many practical implications for both sports coaching and strength and conditioning practice.
6.4.1 Biomechanics of the Block Start

Of the numerous studies that have investigated the biomechanics of the block start (e.g. Bezodis et al., 2015; Mero et al., 2006; Otsuka et al., 2014; Slawinski et al., 2010b; Willwacher et al., 2016), to the best of the author’s knowledge, none have undertaken a detailed investigation into the joint kinetic demand of executing this task. The current study addressed this gap in the literature by employing novel instrumented starting blocks to aid the quantification of front and rear leg joint moment, power and work, so that musculoskeletal demand could be explained and understood (Chapter 3; Brazil et al., 2017). New insights into the magnitude of these joint kinetic variables was provided, as well as detailing the relatively high extensor energy generating capacity of the hip joint towards overall leg extensor energy generation (~60%). Further novel insights were provided by comparing musculoskeletal demand between the front and rear leg, which demonstrated that the main source of joint kinetic asymmetry manifested at the knee joint.

The second phase of Chapter 3 provided new understanding of the key determinants of block start performance, continuing and extending beyond previous studies of external kinetics (Fortier et al., 2005; Otsuka et al., 2014; Willwacher, Herrmann, Heinrich et al., 2013; Willwacher et al., 2016). The importance of maximising total horizontal external force (Willwacher et al., 2016) was supported in the current study, although novel information suggesting individual preference for front/ rear force production was shown. The current research continued to identify those joint kinetic techniques associated not only with performance, but also the magnitude of horizontal force applied to each block (Chapter 3; Brazil et al., 2018). Whilst individual bivariate correlations with average \(F_Y\) provided specific knowledge of the joint kinetic determinants of individual block force production, multiple regression analysis revealed that 60% of block start performance was explained by the average extensor moment at the rear ankle and front hip joint, and peak extensor power generation at the front knee joint.

Given the additional insights into movement organisation and control that can be obtained from understanding movement coordination (Bernstein, 1967; Kugler et al., 1980; Newell, 1986; Turvey, 1990), Chapter 4 continued to progress knowledge of the block start by quantifying intra-limb joint coordination and variability, applying vector coding analysis to this unique setting. Results of this analysis demonstrated the emergence of consistent proximal extension and in-phase extension.
coordinative patterns at the front leg (Fig. 4.6), that could be viewed as task specific co-
ordinative structures (Moir et al., 2018). Intra-limb joint coordination variability was shown to be highest at the onset of movement, supporting the observations of Wilson et al. (2016) that flexibility is required when physical demand increases and the state of a system is undergoing abrupt change (Haken et al., 1985; Heiderscheit, 2000). Further insight towards the techniques associated with superior performance were identified through individual inspection of coordination profiles, with front leg K-A distal extension found to be more prominent amongst athletes who produced higher magnitudes of NAHP. To the author’s knowledge, the current study provided the first investigation of intra-limb coordination and variability and findings provided a unique contribution to knowledge of block start biomechanics.

The implications of the current findings are twofold: 1) enabling sprints coaches to increase their fundamental knowledge of block start biomechanics, and 2) providing strength and conditioning practitioners with information to target physical development to the key determinants of performance. The use of biomechanical analyses in the current research can be used by practitioners to develop their tacit knowledge of the block start, influencing their perception of this sports skill and the strategies that can be implemented to increase its performance.

6.4.2 Theoretical Framework for Exercise Selection

The experimental framework adopted in the current thesis highlighted how biomechanical analyses can help advance the theoretical and practical understanding of the principles of training in regards to exercise selection for enhancing the transfer of training to improved sports performance. Biomechanical similarity between a training exercise and target skill has been widely regarded to facilitate the transfer of training through the principle of specificity (Cormie et al., 2011b; Siff, & Verkoshansky, 1999; Stone et al., 2002). However, the importance of dissimilarity with respect to the principle of overload (Matveyev, 1981) is necessary to ensure neuromuscular-skeletal adaptations can increase an athlete’s motor potential and allow them to overcome their limitations to performance (Moir et al., 2018). It was therefore essential that both principles of overload and specificity be investigated concurrently when evaluating the potential effectiveness of a particular training exercise (Chapter 5).
Based on the principles of overload and specificity, Chapter 5 presented two themes for comparing training exercises with a competitive motor task: **musculoskeletal demand** and **movement dynamics**. The two themes were founded on the requirement of strength training to alter an individual’s organismic constraints to overcome their biological limitations of performance (Moir et al., 2018), as well as promoting competition task specific joint coordination patterns to facilitate the positive transfer of training (Bobbert, & Van Soest, 1994).

Through interrogation of joint kinematics and kinetics, novel insight into the nature of musculoskeletal overload was gained in Chapter 5. By utilising discrete and continuous analyses, the magnitude and locality of joint kinetic overload alongside similarity in joint angle could be established. Results highlighted that the exercise able to elicit the greatest overload was dependent on the specific joint and variable of interest and individual athlete. The emergence of all exercises possessing aspects of joint kinetic overload that were relevant to performance, brought into question contemporary views on exercise specificity classification (Wild et al., 2011; Young et al., 2001), by evidencing the potential of all exercises to elicit adaptations that were relevant to the biomechanical determinants of the competitive motor task. The importance of employing multiple exercise modes to alter an athlete’s organismic constraints to facilitate improved sports performance was thus supported (Cormie et al., 2011b).

Utilising a coordinative approach to quantify similarity in movement pattern between the block start and training exercises further questioned modern exercise categorisation on a spectrum of specificity based on global replication of a competitive skill (Bondarchuck, 2007; Crick, 2009). From this unidimensional concept of specificity being based on replication alone, the split stance horizontal jump exercises (HJSP and MBDSP) would be classed as most specific, with BS90 being least specific (Crick, 2009; Wild et al., 2011; Young et al., 2001). However, CA_DIF and continuous analysis of CA profiles refuted this notion, as JS0, JS60 and BS90 often showed greater similarity with the emergent coordination patterns in the block start (Chapter 5).

Therefore, the current study warranted reconceptualisation of what constitutes a ‘sport-specific’ training exercise. For example, BS90 was able to elicit joint angle specific extensor moment overload of the front leg knee and hip joint, whilst eliciting
competition task specific coordination patterns. Whilst traditionally this exercise would be classes as non-specific training method for sprinting (Crick, 2009), results would indicate this exercise provides a specific means of increasing knee and hip extensor strength with respect to the block start. To advance the objective selection of training exercises, an exercises global level of ‘specificity’ should emerge through the nature of overload with respect to the biomechanical determinants of performance, alongside replication of competition task-specific coordinative structures. The results of Chapter 5 highlighted the need for comprehensive, holistic approaches to investigate the training principles of overload and specificity, in order to provide strength and conditioning practitioners with an adequate evidence base to select strength training exercises.

The current research showed that the training principles of overload and specificity were dependent on the task demands and individual organism (athlete). Therefore, the principles of training (Matveyev, 1981; Siff, & Verkoshansky, 1999) are better understood in the constraints based approach to motor control theory (Newell, 1986), by which the overload and specificity characteristics of a training exercise will be dependent on the interaction of an organism (individual) within their environment to execute the particular motor task. Integrating the theoretical basis of the principles of training (Matveyev, 1981; Siff, & Verkoshansky, 1999) in a constraints led context (Newell, 1986) may provide the best framework to objectify exercise selection in strength and conditioning (Fig. 6.1), understanding that both overload and specificity are required to develop an organism to execute a competitive motor task to a higher level of performance.
Figure 6.1. Proposed exercise selection framework based on the principles of overload and specificity within the context of Newell’s (Newell, 1986) model of constraints on action.

In this framework, the type of exercise would first be selected based on the desired change in organismic constraints related to the biomechanical determinants of performance. The final decision is then made based on the replication of competition task-specific coordinative structures, so that altered organismic constraints can have the best chance of being effectively utilised in the constraints of the competitive motor task (Bobbert, & Van Soest, 1994; Verkoshansky, 2011). The proposed framework of exercise selection recognises that to enhance performance, the principles of overload and specificity should be synergistic, in order for adaptations to occur that influence the interaction between an organism and the task (Fig. 6.1). At both stages, the selection of exercises will be influenced by the individual athlete. Of utmost importance is the use of biomechanical analyses to support this process, to identify the biomechanical determinants of a competitive motor task and provide objective evidence to assist each selection stage. It is therefore imperative that biomechanical analyses be embedded into strength and conditioning practice.
6.4.3 Development of Research Philosophy

Centred on biomechanical technique analysis and dynamical systems theory, within an ecologically valid setting, a research philosophy emerged to develop training theory and the framework of exercise selection to enhance sports performance. At the joint level of mechanics, biomechanical analysis can reveal the nexus between overload and specificity within a self-organising coordinated motor system, to unlock the mechanisms underlying effective exercise selection.

The work of this thesis established a framework for biomechanics to support exercise selection within physical preparation for any competitive motor task. By applying this framework, biomechanists can understand both the musculoskeletal and movement dynamics characteristics of the sports skill and training tasks, as well as developing an understanding of the biomechanical determinants of performance that can lead to establishing individual biomechanical limitations. Combining this biomechanical knowledge with a reconceptualised interpretation of a ‘sport-specific exercise’ can permit the objective selection of exercises that stimulate relevant neuromuscular-skeletal adaptations with the greatest potential to enhance sports performance.

6.5 Future Directions

This research utilised intra-limb joint coordination analysis to investigate the organisation and control of movement and inverse dynamics procedures to quantify the net mechanical output at each joint. Whilst combining these analysis themes has provided a comprehensive joint-level understanding of the principles of training within exercise selection, deeper investigation at the muscle-tendon unit is required.

For example, an EMG analysis could be utilised to gain insight into the muscles contributing to the observed joint kinetics (Hanley, & Bissas, 2013; Jacobs, & van Ingen Schenau, 1992; Kuitunen et al., 2002), as well as improving understanding of inter-muscular coordination that has been theoretically linked with training transfer (Bobbert, & Van Soest, 1994). Furthermore, estimations of muscular force through musculoskeletal modelling may reveal the exact muscular effort required to perform motor tasks and a more detailed insight towards the nature of adaptation through resistance training (Bryanton, Carey, Kennedy & Chiu, 2015; Chiu, 2018; Schellenberg, Oberhofer, Taylor & Lorenzetti, 2015; Schellenberg, Taylor &
Lorenzetti, 2017). However, in the current research, analysing intra-limb joint coordination and variability, alongside net joint moment and power, was sufficient to gain greater insight into the principles of training underpinning exercise selection.

The cross-sectional study design adopted in this research has provided observations at a specific point in time in a subset of male sprinters representative of national and international level performers. Whilst this type of study design is frequently utilised in applied biomechanics research (Bezodis et al., 2014; Exell et al., 2012; Irwin et al., 2007; Wilson et al., 2008), chronic studies are required to truly understand which exercises are most effective for enhancing sports performance when utilised within an athlete's periodised training programme. Whilst beyond the scope of the current research, longitudinal analyses accompanied with understanding of the exact nature of muscle-tendon unit adaptation resulting from training, would provide the extra level of detail required to bridge the gap between theory and practice. This approach would also enlighten biomechanists and coaches on the exact changes in movement coordination that may occur through training, and whether promoting sport specific coordinative structures in training can facilitate the effective utilisation of altered organismic constraints within the competitive motor task (Bobbert, & Van Soest, 1994; Burnie et al., 2017).

The framework presented in the current research for understanding the theoretical underpinnings of effective exercise selection could be utilised in future investigations to determine the relevance of a greater range of exercises in relation to the block start. Gathering information on the musculoskeletal demand and movement dynamics characteristics of a greater pool of exercises in each category (heavy resistance, ballistic, plyometric etc.) would afford strength and conditioning practitioners with a catalogue of exercises most relevant to enhancing the biomechanical determinants of block start performance. Furthermore, the knowledge of block start technique gained throughout the current research could be utilised to innovate training exercises that can encourage musculoskeletal overload in a task specific manner, to elicit favourable adaptations for improving performance. In addition, the current thesis has provided a framework of biomechanical analyses to compare any competitive and training motor tasks, in order to inform exercise selection based on integrating the principles of training, dynamical systems theory and transfer of training.
6.6 Thesis Conclusion

Utilising biomechanical technique analysis and dynamical systems theory, this research has explored and advanced theoretical understanding of the training principles of overload and specificity within exercise selection, and has achieved the aim of the thesis. The aim was addressed by constructing a two-phase analysis approach (Technique Analysis: Biomechanics, Training Principles: Biomechanics Interface) and addressing specific research questions within each phase. By quantifying the biomechanics of a competitive motor task and the characteristics associated with superior performance, from a musculoskeletal (Chapter 3) and intra-limb joint coordination (Chapter 4) perspective, a foundation of knowledge was provided to explore and advance the principles of training within exercise selection.

In Chapter 5, a framework was developed to explore the interface between biomechanics and training theory, which identified that overload characteristics of a training exercise were dependent on the particular biomechanical determinants of performance and individual athlete. Utilising an intra-limb joint coordination approach to movement specificity (Irwin & Kerwin, 2007a; Romanazzi et al., 2015; Wilson et al., 2009) demonstrated that traditionally viewed non-specific exercises were shown to promote the self-organisation of multiple degrees of freedom into competitive task specific coordinative structures (Bernstein, 1967; Kugler et al., 1980). The current research therefore challenged contemporary approaches to exercise categorisation within sprint running (Crick, 2009; Wild et al., 2011; Young et al., 2001), and encouraged a nexus of overload and specificity within a constraints led approach (Newell, 1986), to understand the most appropriate exercises to facilitate task relevant organismic adaptations that can transfer into improved sports performance.

To conclude, the development of block performance (task constraints) is founded upon high levels of neuromuscular strength and power (organismic constraints). The incorporation of strength training into an athlete's training programme is therefore required to develop these organismic constraints (overload), to increase an athlete's motor potential to execute a sports skill to a higher level of performance. Ensuring similarity in the coordinative dynamics between training and competitive motor tasks (movement specificity), may enable changes in organismic constraints to be effectively utilised in the competitive task by promoting the emergence of task specific coordinative structures. By integrating traditional theories of training
(Matveyev, 1981; Siff, & Verkoshansky, 1999), with the constraints based approach to human movement (Newell, 1986), the current research encouraged a reconceptualisation of what constitutes a ‘sport specific’ training exercise, and facilitated evidence based decisions within exercise selection to enhance the biomechanical determinants of sports performance.

By undertaking this research, a framework has been established to inform the process of exercise selection to enhance sports performance. Utilising a combined biomechanical and dynamical systems approach, the current research was able to bridge the gap between biomechanics and motor control within the context of the principles of training for the physical preparation of athletes. Subsequent research should aim to investigate the nature of training induced adaptations that can influence sports performance. The findings of this research can influence how scientists, coaches and athletes utilise biomechanical processes to enable objective decisions regarding exercise selection to enhance human performance.


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